	Hits	Search Text	DBs
1	4282	((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.	USPAT; US-PGPUB
2	388	(((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) DMD)	USPAT; US-PGPUB
3	192	(((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) (deformable adj mirror adj display))	USPAT; US-PGPUB
4	389	((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) DMD)) ((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) (deformable adj mirror adj display)))	USPAT; US-PGPUB
5	1	(((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) DMD)) ((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) (deformable adj mirror adj display)))) and (pivo$4 near4 side)	USPAT; US-PGPUB
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7	55	hornbeck.in.	USPAT; US-PGPUB

	Hits	Search Text	DBs
8	392	((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) DMD)) ((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) (deformable adj mirror adj display)))	USPAT; US-PGPUB
9	2	(((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) DMD)) ((((345/204,55,84,85,108) or (348/771) or (359/838,237) or (359/295,291,293,224,230,254,846) or (427/162)).CCLS.) and ((micro near5 mirror) (deformable adj mirror adj display)))) and (pivo$6 near6 length$4)	USPAT; US-PGPUB
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11	1	6007208.URPN.	USPAT
12	1	6198565.URPN.	USPAT

United States Patent [19]

Tang et al.

[11] **Patent Number:** **5,025,346**

[45] **Date of Patent:** **Jun. 18, 1991**

[54] **LATERALLY DRIVEN RESONANT MICROSTRUCTURES**

[75] Inventors: **William C. Tang**, Emeryville; **Roger T. Howe**, Lafayette, both of Calif.

[73] Assignee: **Regents of the University of California**, Oakland, Calif.

[21] Appl. No.: **312,642**

[22] Filed: **Feb. 17, 1989**

[51] **Int. Cl.**[5] **H01G 7/00; G01P 15/08**
[52] **U.S. Cl.** .... **361/283**; 73/517 AV
[58] **Field of Search** .... 361/283, 286, 296, 297, 361/298; 73/336.5, 517 AV, 704

[56] **References Cited**

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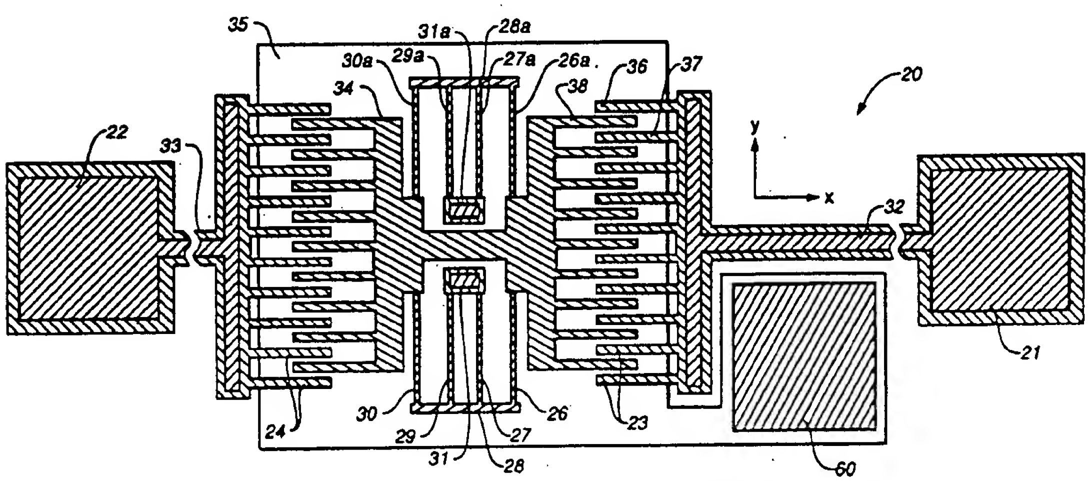
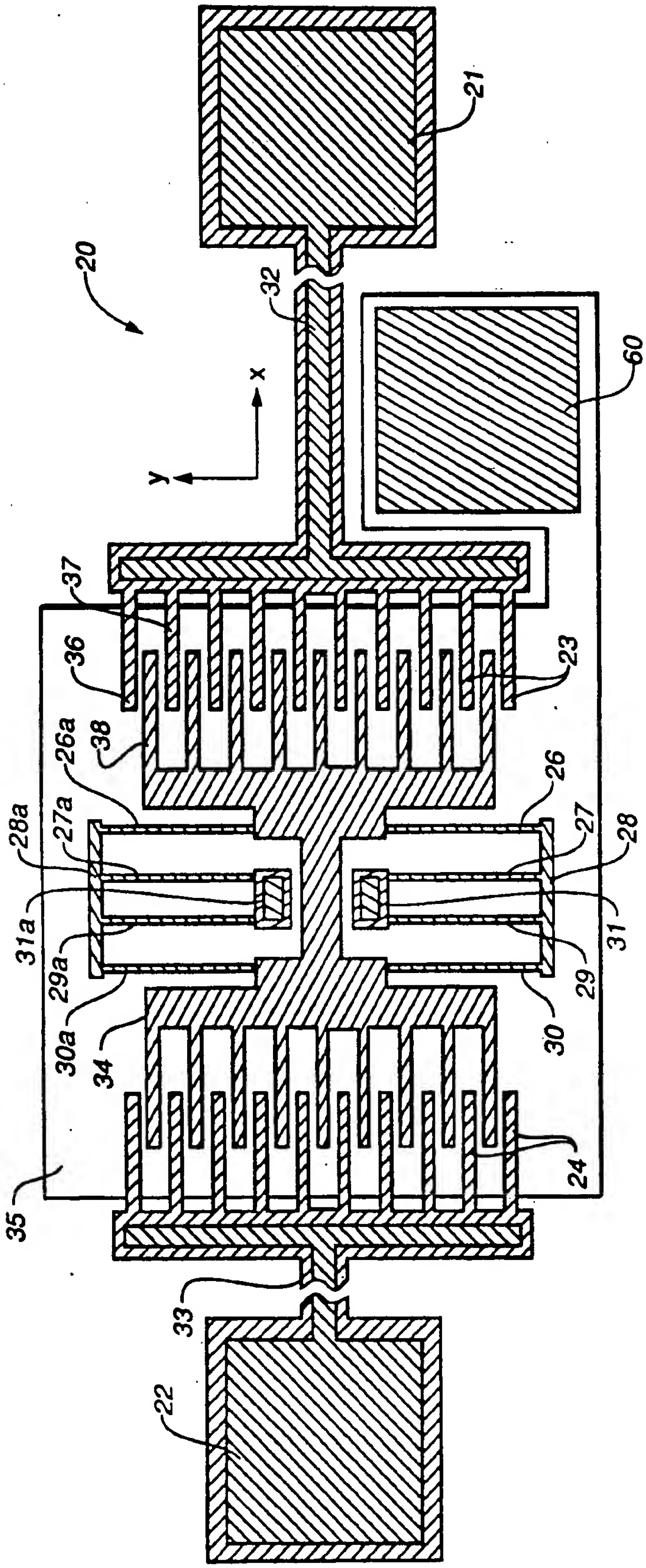
Primary Examiner—Donald A. Griffin
Attorney, Agent, or Firm—Owen, Wickersham & Erickson

[57] **ABSTRACT**

A microbridge device for use as a sensor or an actuator is driven parallel to a substrate as a resonant microstructure. The microstructure comprises a stationary thin-film electrode secured to the substrate and located in a plane above it. A movable plate overlaying the substrate is suspended above it. The movable plate and electrode are patterned to provide for each at least one comb with fingers interdigitated with those of the other.

20 Claims, 11 Drawing Sheets




20
21
22
23
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26a
27
27a
28
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32
33
34
35
36
37
38
60
x
y

FIG._1

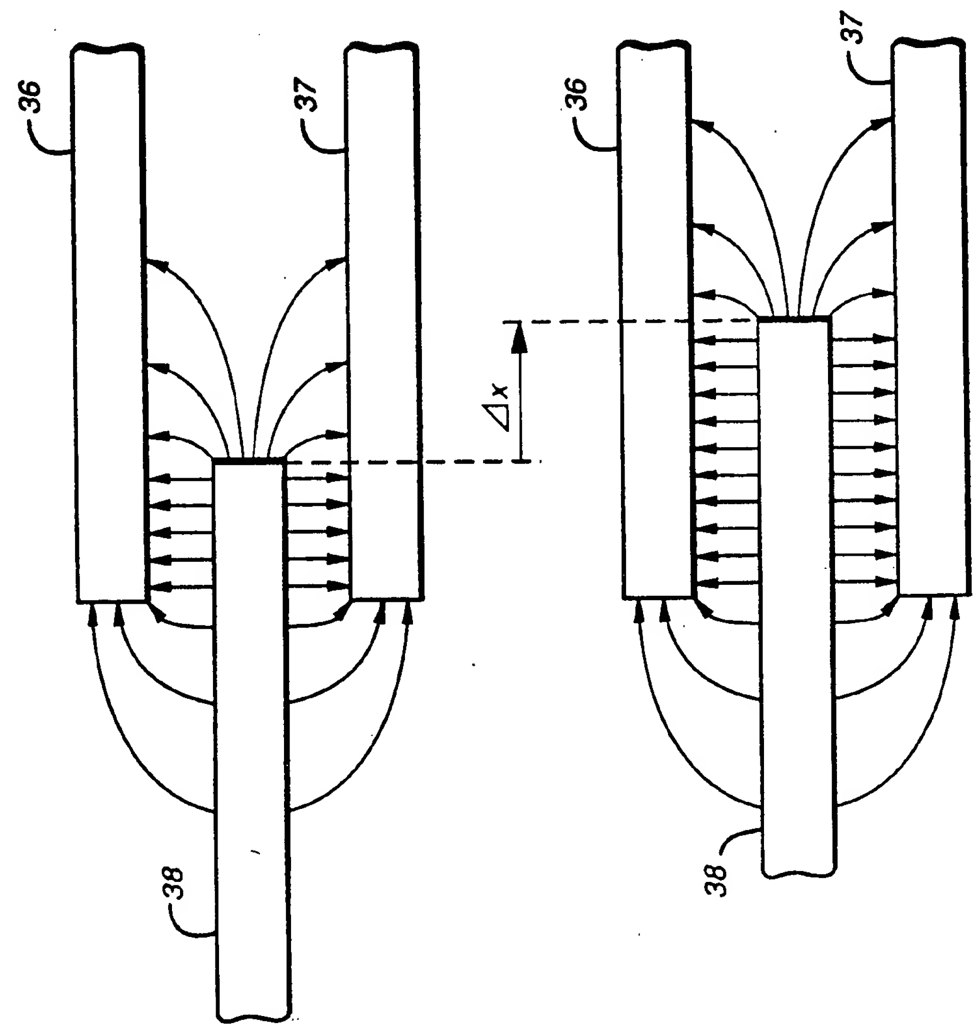

FIG._2

FIG._3

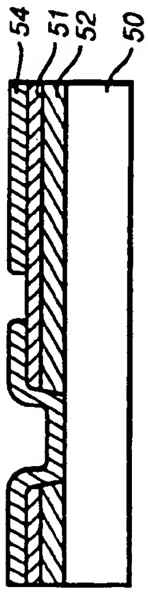

FIG._4D

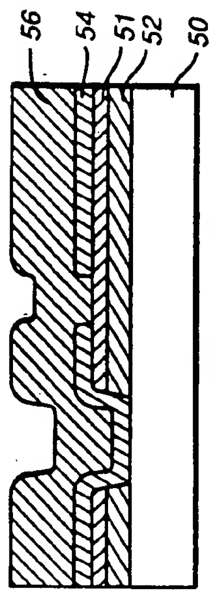

FIG._4E

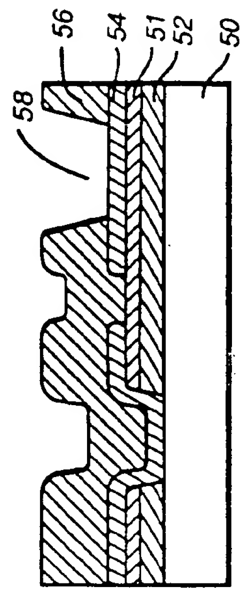

FIG._4F

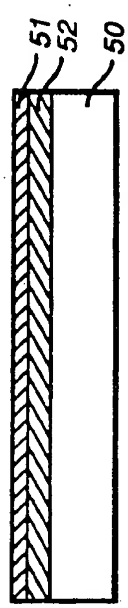

FIG._4A

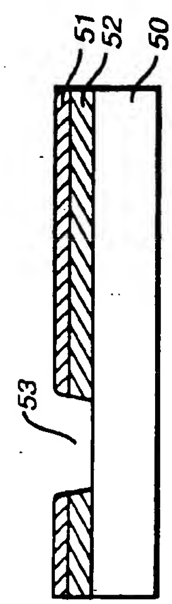

FIG._4B

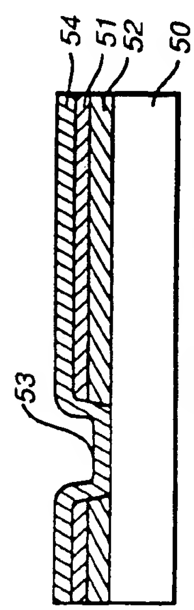

FIG._4C

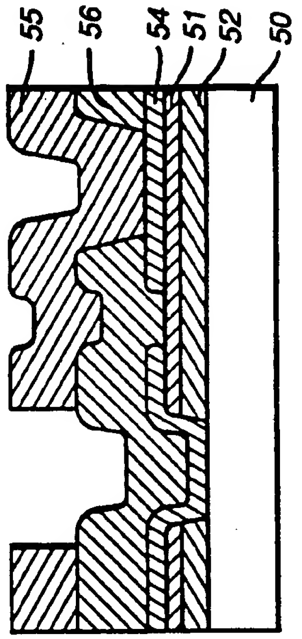

FIG._4I

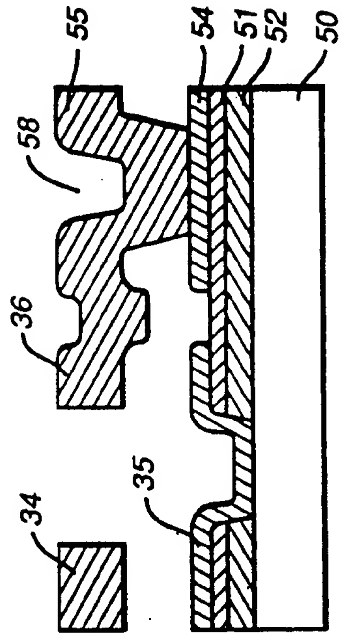

FIG._4J

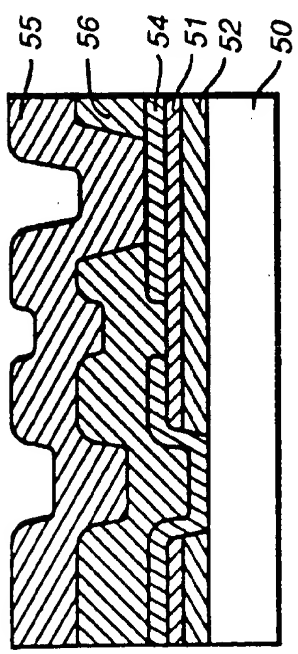

FIG._4G

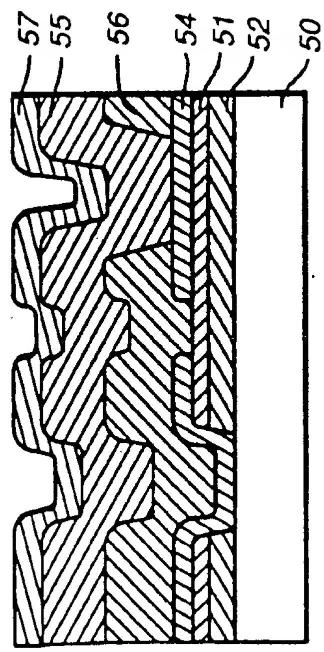

FIG._4H

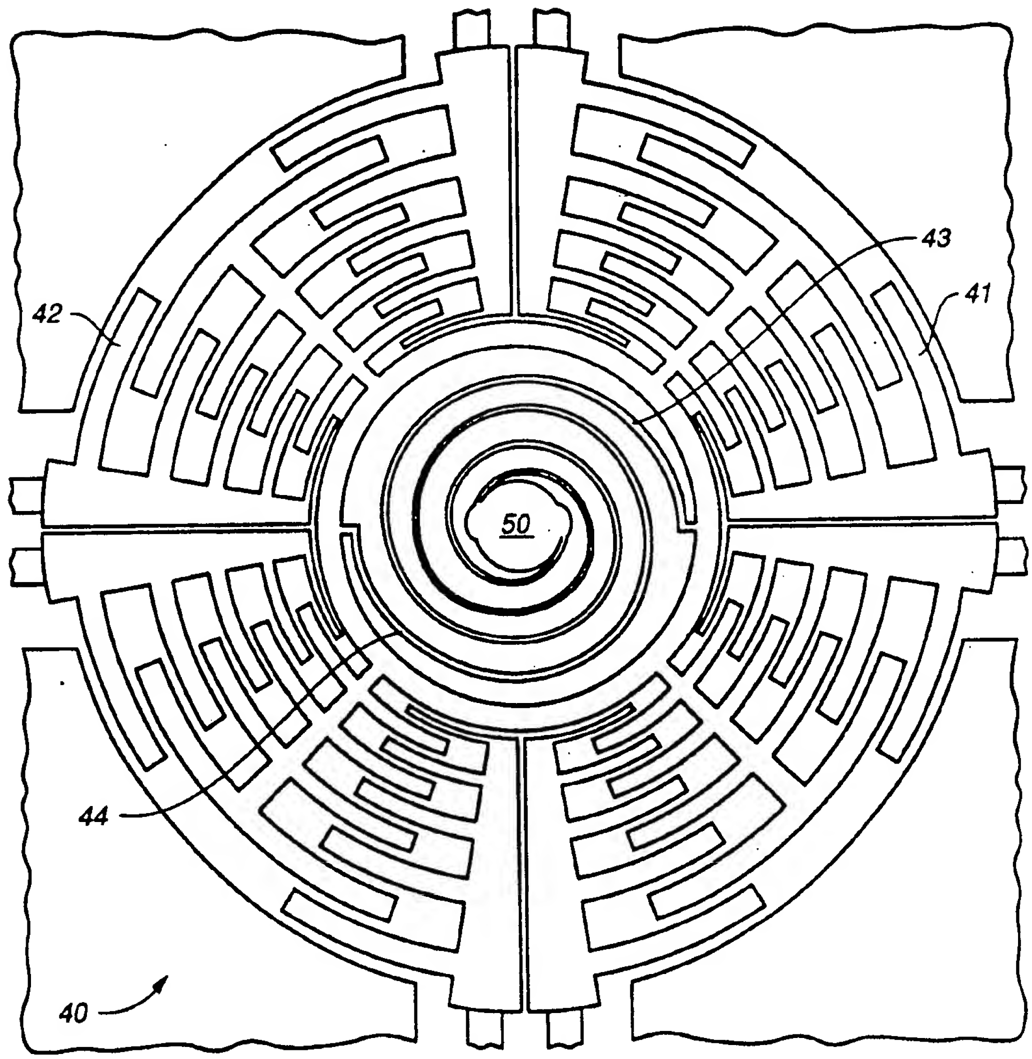

FIG._5

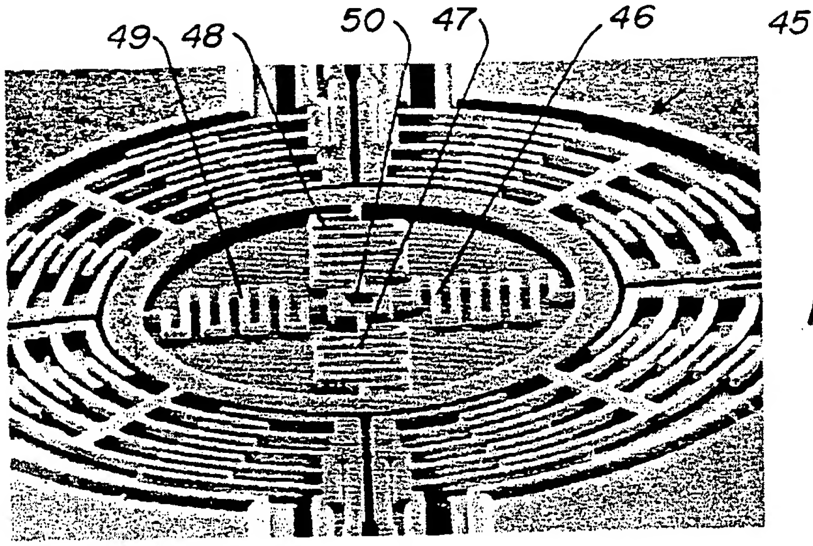

FIG._6

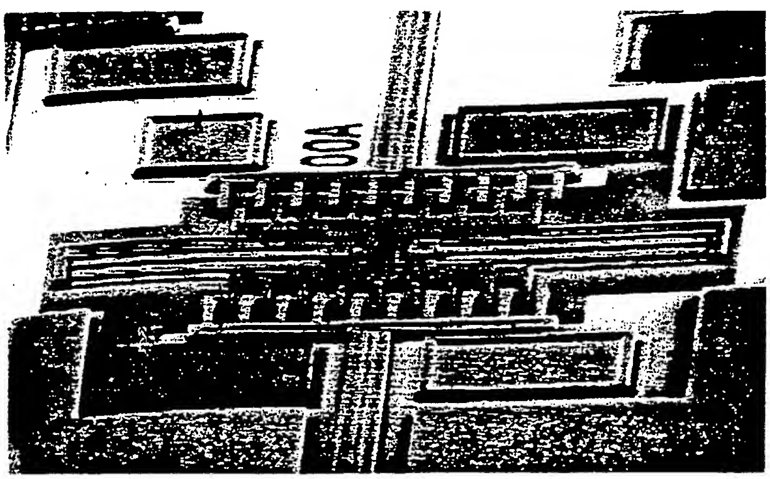

FIG._7

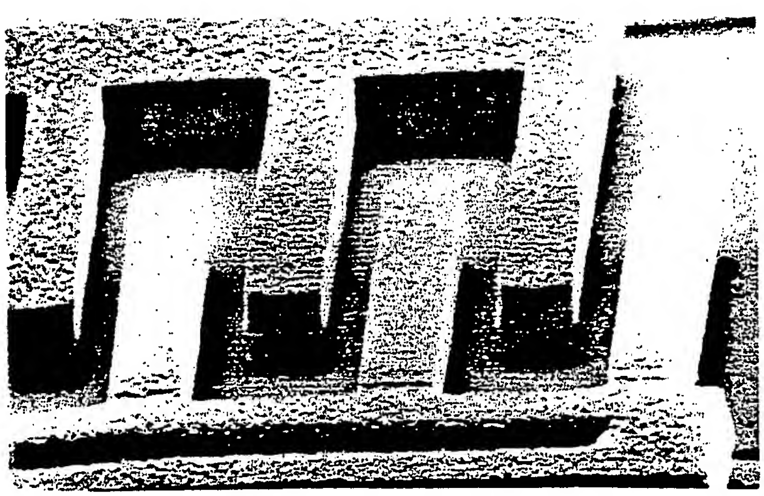

FIG._8

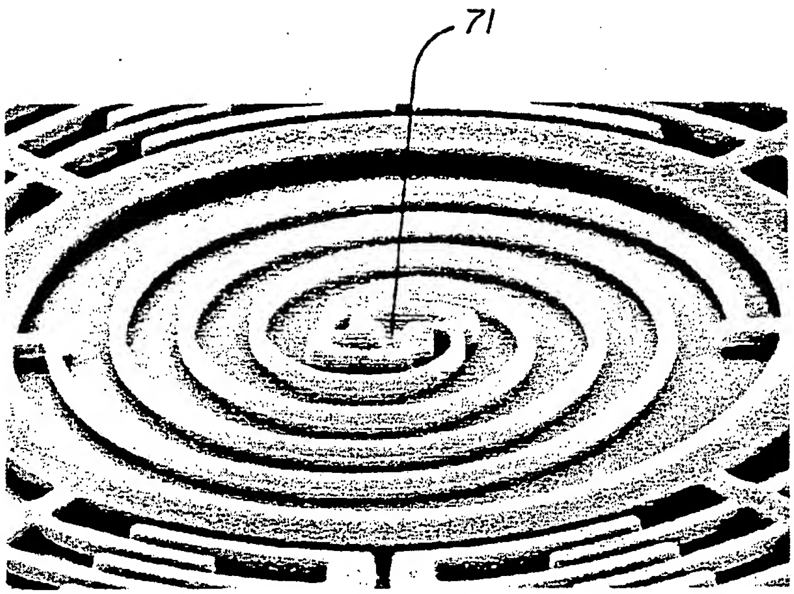

FIG._9

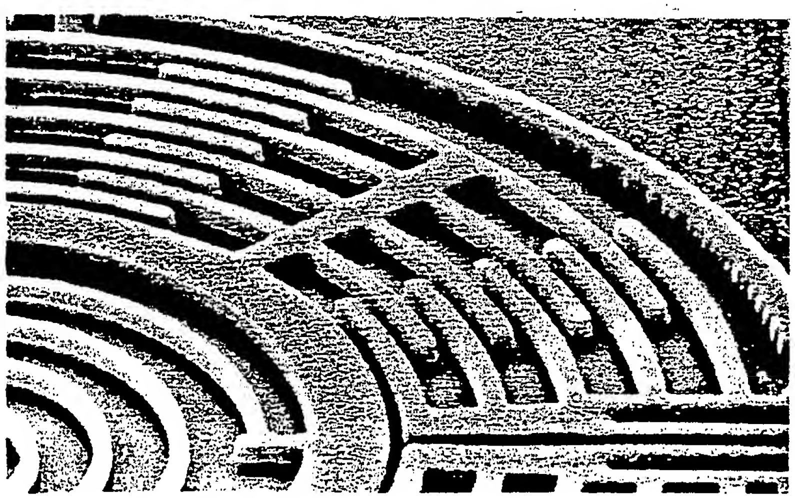

FIG._10

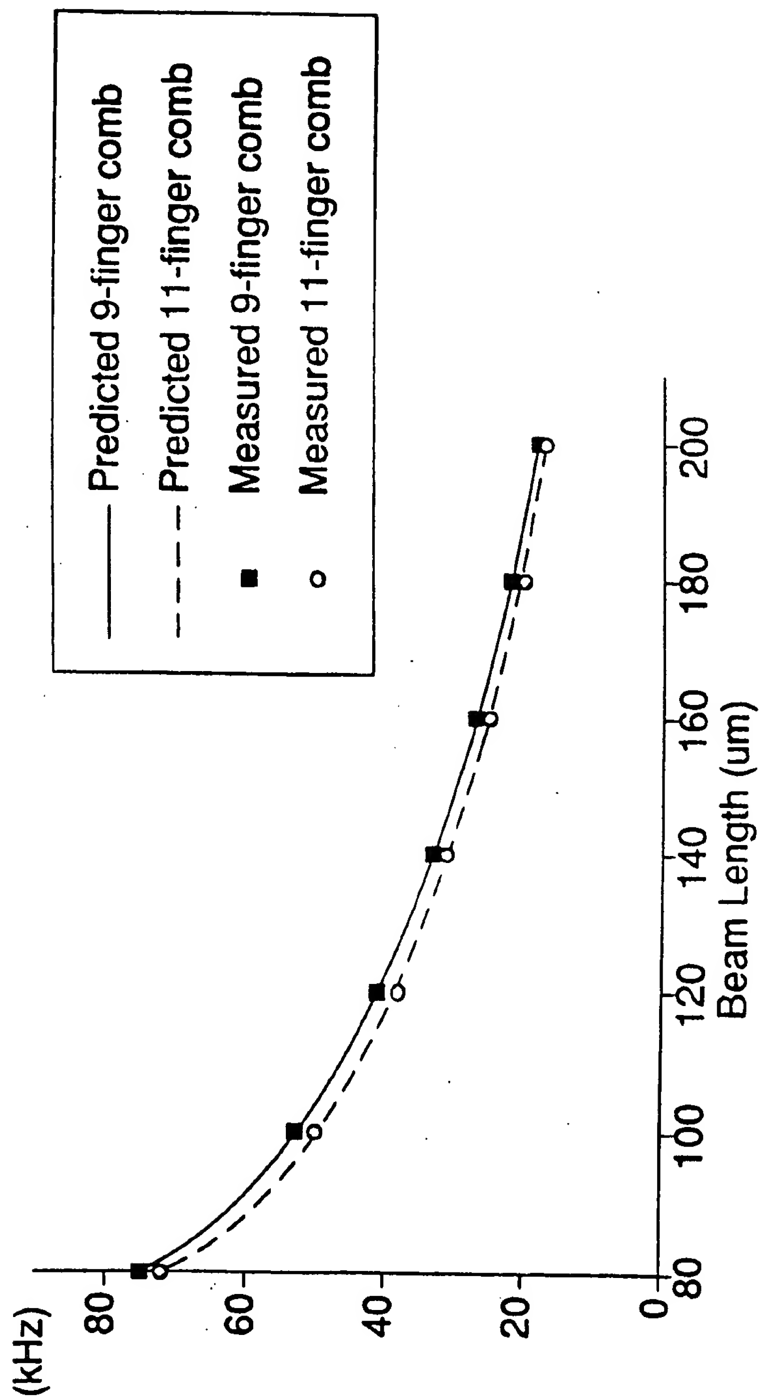
Predicted 9-finger comb
Predicted 11-finger comb
Measured 9-finger comb
Measured 11-finger comb
(kHz)
80
60
40
20
0
80
100
120
140
160
180
200
Beam Length (um)

FIG._11

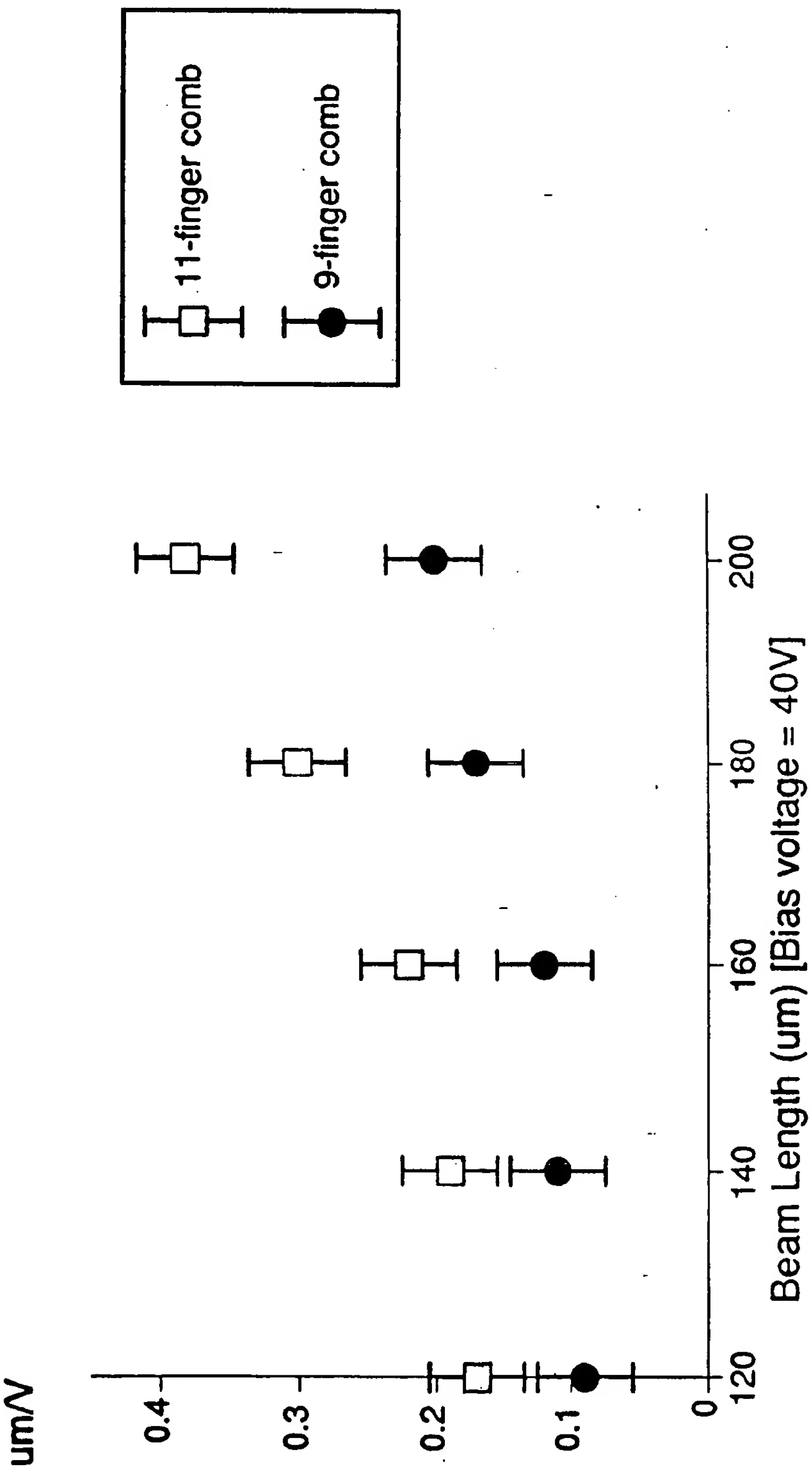
11-finger comb
9-finger comb
um/V
0.4
0.3
0.2
0.1
0
120
140
160
180
200
Beam Length (um) [Bias voltage = 40V]

FIG._12

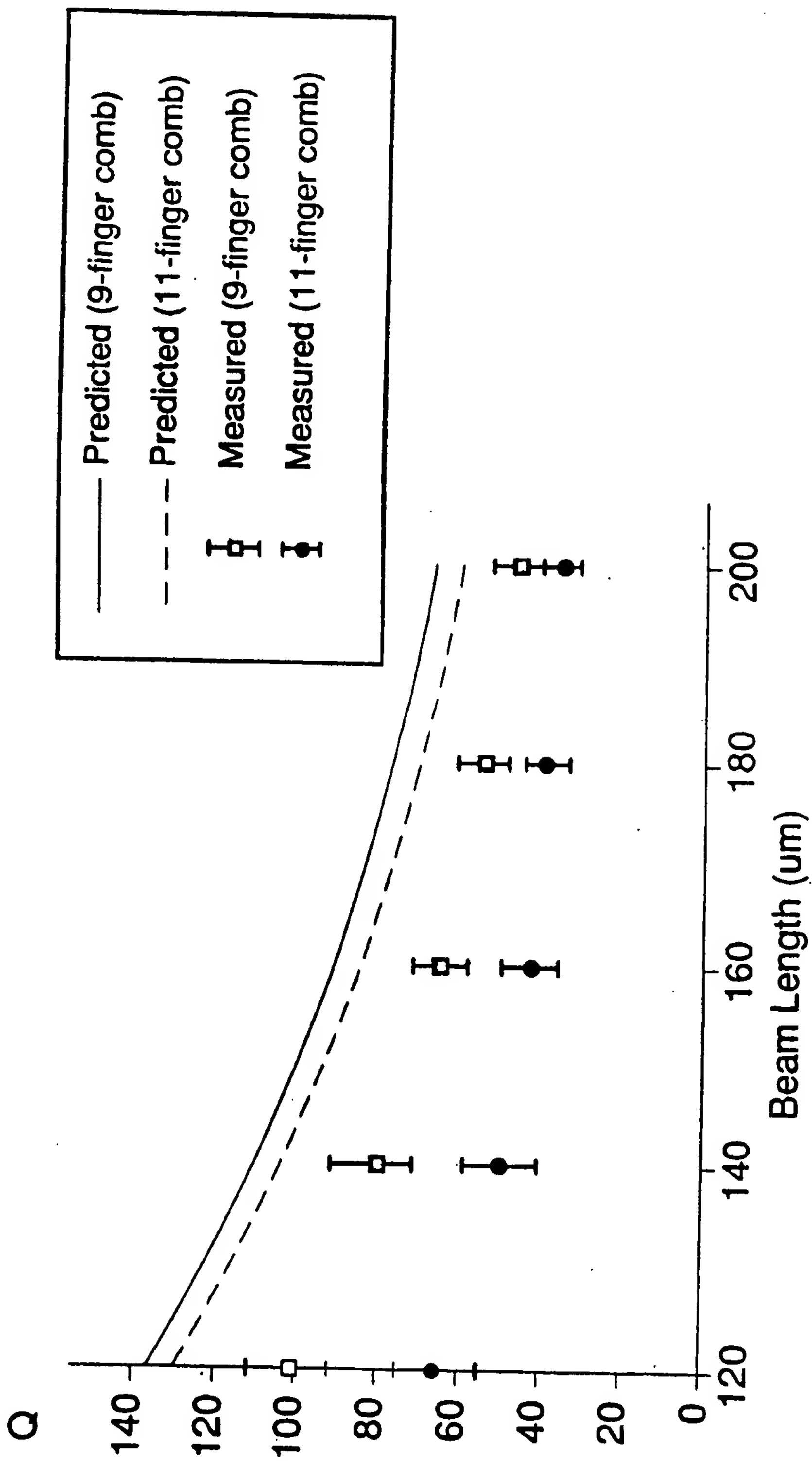
Predicted (9-finger comb)
Predicted (11-finger comb)
Measured (9-finger comb)
Measured (11-finger comb)
Q
140
120
100
80
60
40
20
0
120
140
160
180
200
Beam Length (um)

FIG._13

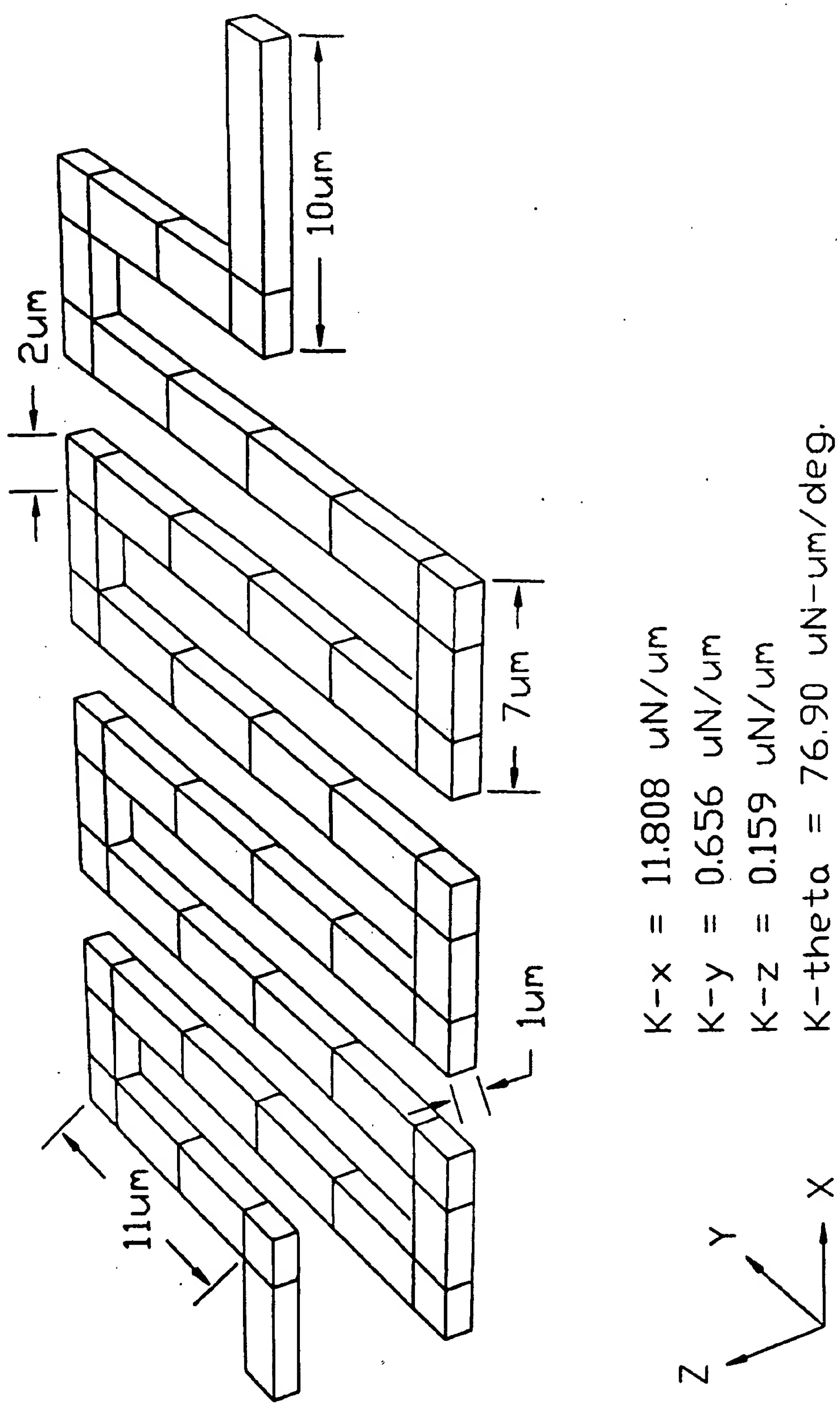
10um
2um
7um
1um
11um
K-x = 11.808 uN/um
K-y = 0.656 uN/um
K-z = 0.159 uN/um
K-theta = 76.90 uN-um/deg.
X
Y
Z

FIG._14

LATERALLY DRIVEN RESONANT MICROSTRUCTURES

This invention was made with Goverment support under Grant Contract No. CDR-86-14900 awarded by the National Science Foundation. The Goverment has certain rights in this invention.

This invention relates to a laterally driven resonant microstructure.

BACKGROUND OF THE INVENTION

Because of the advantages of reliability, low cost, and the potential for achieving high precision microsensors, several attemps have been made to integrate mechanical tuning elements on silicon substrates. A polysilicon microbridge has been driven vertically as a resonant microsensor; it features a simple process that ensures high yield, a high quality factor-Q-in vacuum, and high tunability, by varying physical or chemical parameters.

However, vertically driven microbridges have suffered from several shortcomings. At atmospheric pressure, the Q is severely reduced by viscous damping, usually to less than 20. Furthermore, it requires holding its driving signal to a very small value to sustain resonance in a vacuum, typically on the order of a few millivolts, thereby creating a serious hurdle in designing a stable sustaining amplifier. Because the microbridge is essentially a variable capacitor driven electrostatically, the relationship between the drive signal and the capacitance readout is highly nonlinear, presenting a challenging problem for the sense circuit.

SUMMARY OF THE INVENTION

The present invention comprises a polysilicon microbridge which is driven parallel to the substrate as a resonant microstructure. One significant advantage of the lateral-drive concept is that a variety of elaborate geometric structures, such as differential capacitive excitation and detection, can be incorporated without an increase in process complexity. This flexibility enables the development of microactuators as well as microsensors based on lateral resonant structures. The performance of micromechanical resonant structures is improved by applying lateral electrostatic forces, i.e., forces parallel to the plane of the substrate. A microfabrication process of the invention uses a single polysilicon thin film that is patterned as both a stationary electrode for applying lateral electrostatic forces and as the micromechanical resonant structure, therefore, eliminating mask-to-mask misalignment for critical features.

Such electrostatic forces are used to drive lateral resonant modes of micromechanical structures. They have several advantages over the vertical resonant modes, which are perpendicular to the plane of the substrate. When operated at atmospheric pressure, lateral resonant modes have much higher quality factors (Q) than do vertical modes. In addition, the lateral drive approach enables large, linear drive voltages, larger amplitude vibrations, small electrical feedthrough, and easier excitation and detection of resonant frequencies.

Thus, interdigitated finger structures or combs can be effective for electrostatically exciting the resonance of polysilicon microstructures parallel to the plane of the substrate. Linear plates suspended by a folded-cantilever truss and torsional plates suspended by spiral and serpentine springs are fabricated from a 2 μm-thick phosphorus-doped LPCVD polysilicon film. Resonance can be observed visually, with frequencies ranging from 18 kHz to 80 KHz and quality factors from 20 to 130. Simple beam theory is adequate for calculating the resonant frequencies, using a Young's modulus of 140 GPa and neglecting residual strain in the released structures.

In such a lateral-drive approach, a mechanical structure is or can, as stated, be driven parallel to the substrate by a linear comb drive.

There are three main advantages of this new, lateral-drive structure.

(1) At atmospheric pressure, a much higher Q can be obtained than with a vertically-driven structure, because of lower damping in the lateral structure. Since the plate is suspended about 2–3 μm above the substrate, it is much easier to slide the plate parallel to the substrate than to pump air in and out from beneath the plate in vertical motion.

(2) Complicated planar geometries such as the linear comb drive can be designed without adding processing steps. The comb drive of this invention provides a linear relationship between the induced electrostatic force and the applied voltage. The operation of the comb drive is described herein.

(3) Since the structure is driven with fringing fields, convenient drive voltages on the order of volts, instead of millivolts, can be used, even in a vacuum. In vacuum without any air damping, a vertically driven bridge is usually too sensitive to applied voltage, so that the voltage must be limited to a few millivolts; such a limitation creates problems in designing a stable circuit to provide the low drive voltage.

The limitations of the vertically driven structure emphasize the advantages of the lateral-drive approach, in which the mechanical structure is driven parallel to the substrate. As the structure is designed to be driven with fringing fields, conventional drive voltages of the order of volts can be used. Also complicated geometries can be designed without adding processing steps,—a distinct advantage. This flexibility enables the use of resonant elements with high linearity, high detection sensitivity, useful oscillation amplitudes, and good isolation between the drive signal and the sense signal. The same flexibility enables resonant structures to be designed to oscillate either linearly or torsionally.

At atmospheric pressure, the Q of the lateral mode of oscillation is dominated by viscous drag in the cavity beneath the structure. Since the drag on a plate in Couette flow is far less than the viscous damping of a plate in vertical motion, a much higher Q is obtained by driving in the lateral mode. This phenomenon has been independently recognized in the development of a micro floating-element, skin friction sensor with suppressed response to pressure fluctuations.

Additional design criteria make possible more sophisticated devices. The design theory and simulation results of the more sophisticated structures feature an enhanced comb drive, stress-released beam supports, improved electrostatic shielding, and torsional plates with differential drive and sense ports.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a comb drive structure embodying the principles of the invention.

FIG. 2 is a plan view of a simplified comb drive structure for linearity calculation, shown in a first position.

FIG. 3 is a similar view showing the simplified comb drive structure in a second position.

FIG. 4 is a series of steps for microstructure fabrication. FIG. 4(*a*) shows a preforming step in which a layer of silicon nitride is deposited on top of a layer of silicon dioxide. FIG. 4(*b*), a first masking step with windows opened in a nitride and an oxide (silicon dioxide) layer on a silicon substrate. Further steps are shown at FIGS. 4(*b*), 4(*c*), 4(*d*), 4(*e*), 4(*f*), 4(*g*), 4(*h*), 4(*i*), and 4(*j*).

FIG. 5 is a plan view of a spiral-supported torsional resonant plate.

FIG. 6 is a scanning electron micrograph of a serpentine spring supporting a torsional resonant plate.

FIG. 7 is a scanning electron micrograph of a linear resonant structure.

FIG. 8 is a scanning electron micrograph of the linear comb drive structure.

FIG. 9 is a scanning electron micrograph of two two-turn Archimedean spirals supporting a torsional resonant plate.

FIG. 10 is a scanning electron micrograph of the concentric comb structure.

FIG. 11 is a graph of the predicted and measured resonant frequencies for the two types of linear resonant plates with beam lengths ranging form 80 μm to 200 μm.

FIG. 12 is a graph of measured transfer functions for two types of combs with different beam lengths.

FIG. 13 is a graph of predicted and measured quality factors for two types of combs with different beam lengths.

FIG. 14 is a perspective view of the serpentine spring support for the torsional resonant plate, indicating the dimensions and simulation results for the spring constants.

DESCRIPTION OF SOME PREFERRED EMBODIMENTS

FIG. 1 shows the layout of a linear resonant structure **20** of this invention which can be driven electrostatically from one side **21** and sensed capacitively at the other side **22** with interdigitated finger (comb) structures (**23** and **24**). Alternatively, the structure **20** can be driven differentially (push-pull) using the two combs **23** and **24**, with the motion sensed by an impedance shift at resonance (not shown). In analyzing the electromechanical transfer function, the former, two-port configuration is considered. The motion is sensed by detecting the short-circuit current through the time-varying interdigitated capacitor **24** with a dc bias. The driving force and the output sensitivity are both proportional to the variation of the comb capacitance C with the lateral displacement x of the structure. A key feature of the electrostatic-comb drive is that $(\partial C/\partial x)$ is a constant, independent of the displacement x, so long as x is less than the finger overlap (**25**) (see FIG. 2). Therefore, electrostatic-comb drives can have linear electromechanical transfer functions for large displacements, in contrast to parallel-plate capacitive drives.

At the sense port **22**, harmonic motion of the structure in FIG. 1 results in a sense current is which is given by

$$I_s = V_S(\partial C/\partial x)(\partial x/\partial t), \tag{1}$$

where V_s is the bias voltage between the structure **20** and the stationary sense electrode **22**. At the drive port **21**, the static displacement x as a function of drive voltage is given by

$$x = \frac{F_x}{k_{sys}} = \frac{\frac{1}{2}v_D^2(\partial C/\partial x)}{k_{sys}}, \tag{2}$$

where F_x is the electrostatic force in the x-direction, k_{sys} is the system spring constant, and v_D is the drive voltage.

For a drive voltage $v_D(t)=V_P+v_d\sin(\omega t)$, the time derivative of x is

$$\begin{aligned}\frac{\partial x}{\partial t} &= \frac{(\partial C/\partial x)}{2k_{sys}}\frac{\partial(v_D^2)}{\partial t} \\ &= \frac{(\partial C/\partial x)}{2k_{sys}}[2\omega V_P v_d\cos(\omega t + \omega v_d^2\sin(2\omega t)],\end{aligned} \tag{3}$$

where the fact the $(\partial C/\partial x)$ is a constant for the interdigitated-finger capacitor **23** or **24** is used. The second-harmonic term on the right-hand-side of Eqn. (3) is negligible if $v_d << V_p$. Furthermore, if a push-pull drive is used, this term results in a common-mode force and is cancelled to first order. At mechanical resonance, the magnitude of the linear term in Eqn. (3) is multiplied by the quality factor Q, from which it follows that the magnitude of the transfer function $T(j\omega_r)=X/V_d$ relating the phasor displacement X to phasor drive voltage V_d at the resonant frequency ω_r is:

$$\left|\frac{X}{V_d}\right| = V_P\frac{Q}{k_{sys}}(\partial C/\partial x). \tag{4}$$

The transconductance of the resonant structure is defined by $G(j\omega)=I_s/V_d$. Its magnitude at resonance can be found by substitution of Eqn. (4) into the phasor form of Eqn. (1):

$$\left|\frac{I_s}{V_d}\right| = \omega V_P V_S\frac{Q}{k_{sys}}(\partial C/\partial x)^2. \tag{5}$$

A planar electrode extends under the comb and plate in FIG. **1**, which can be grounded or set to a dc potential in order to minimize parasitic capacitive coupling between the drive and sense ports. An additional function of this electrode is to suppress the excitation of undesired modes of the structure.

FIG. 1 shows the layout of a linear resonant plate with a 50 μm-long folded-beam suspension **26, 27, 28, 29** and **30**. Motivations for this truss suspension are its large compliance and its capability for relief of built-in residual strain in the structural film. The folded cantilever beams **26** through **30** are anchored near a center **31**, thus allowing expansion or contraction of the four beams **26, 27, 29** and **30** along the y-axis (FIG. **1**). Folded beams **26*a*, 27*a*, 29*a*** and **30*a*** of FIG. **1** operate similarly. Both the average residual stress in the polysilicon structure **20** and stress induced by large-amplitude plate motion is largely relieved by this design. In addition, the long effective support lengths of the beams **26, 27, 29** and **30, 26*a*, 27*a*, 29*a*** and **30*a*** result in a highly compliant suspension. Plates with 200 μm-long trusses are resonated with amplitudes as large as 10 μm. In FIG. 1 are 815 μm-long conducting polysilicon lines **32** and **33**, such that pads **21** and **22** are separated by about 2 mm to minimize the signal feed-through when one is used to sense the motion, with the other as the drive electrode.

The first order stability of the structure can be analyzed with linearized mechanical theory. In order for the plate to move in the y direction and to touch the stationary electrodes, a minimum of four beams must be buckled. A worst-case assumption using Euler's criterion for buckling a pinned-pinned beam results in:

$$F_{cr} = \frac{\pi^2 EWt^3}{12L^2}. \tag{6}$$

Using the dimensions in FIG. 1, Eq. (6) yields a critical buckling force of 2.9 mN in the y direction. Since the structure is symmetrical along the x-axis, there is no net induced force in the y direction (F_y), unless the plate is moved off axis. Using the finite element method to evaluate ($\partial C/\partial y$) as a function of displacement in y, we can find the critical offset in the y direction such that F_y reaches the critical buckling force. Assuming $V_{bias}=10$ V, it is found that in order to induce a net F_y of 2.9 mN, the comb fingers must be moved to within 0.1 μm from the stationary electrodes, which is very unlikely in normal operation.

An accurate analytical expression for the fundamental lateral resonant frequency, f_r, can be found using Rayleigh's Method:

$$f_r = \frac{1}{2\pi}\left[\frac{k_{sys}}{(M_p + 0.3714M)}\right]^{\frac{1}{2}}. \tag{7}$$

where M_p and M are the masses of the plate 34 and of the supporting beams 26, 27, 29 and 30 and 26*a*, 27*a*, 29*a* and 30*a*, respectively. For the folded-beam structure, an analytical expression k_{sys} can be found by assuming that the trusses 28 and 28*a* joining the folded beam segments are rigid:

$$k_{sys}=24EI/L^3=2Eh(W/L)^3. \tag{8}$$

where $I=(1/12)hW^3$ is the moment of inertia of the beams 26 and 26*a* etc. Residual strain in the structure 20 is neglected in finding this expression. Combining Eqs. (7) and (8), it follows that

$$f_r = \frac{1}{2\pi}\left[\frac{2Eh(W/L)^3}{(M_p + 0.3714M)}\right]^{\frac{1}{2}}. \tag{9}$$

The quality factor Q is estimated by assuming that Couette flow underneath the plate 34 is the dominant dissipative process:

$$Q = \frac{d}{\mu A_p}(Mk_{sys})^{\frac{1}{2}}. \tag{10}$$

where μ is the absolute viscosity of air (1.8×10^{-5}N·s·m^{-2}), and d is the offset between the plate and the substrate. Quality factors for lateral motion are much higher than for motion normal to the substrate.

FIG. 2 is an enlargement of a portion of the comb structure 23 in FIG. 1. It shows two stationary electrodes 36 and 37 and a movable finger 38. The electric field lines between the movable finger 38 and the stationary electrodes 36 and 37 are also shown. FIG. 3 shows finger 38 after a displacement of Δx into the slot between the electrodes 36 and 37. The other fingers in FIG. 1 operate similarly.

Another class of structure 40 is driven into torsional resonance by a set, four pairs, of concentric interdigitated electrodes 41 and 42. FIG. 5 shows one of the structures with two Archimedean spirals 43 and 44 as supporting beams. FIG. 6 is a scanning-electron micrograph (SEM) of another structure 45 using four serpentine springs 46, 47, 48 and 49. The structures, 40 and 45 are supported only at their centers 50, enabling some relaxation of the built-in residual stress in the polysilicon structures 40 and 45. An advantage of the torsional approach is that four or more pairs of balanced concentric comb structures can be placed at the perimeter of the ring, providing a high degree of flexibility for differential drive and sense. Since both the drive and the sense ports are differentially balanced, excitation of undesired oscillation modes is avoided and signal corruption by feedthrough is minimized. As with the lateral structure, extensive ground planes are utilized.

The torsional spring constant of the Archimedean spiral 43 or 44 is given by:

$$k_\theta = \frac{EhW^3}{12L}\ (\mu N \cdot \mu m \cdot rad^{-1}), \tag{11}$$

where L is the length of the spiral. As was done for the lateral resonant structures, residual strain in the spiral spring is neglected in the analysis. This assumption will be reexamined in the discussion of the measured resonant frequencies.

The torsional resonant frequency, f_θ, is evaluated by replacing k_{sys} in Eq. (7) with the torsional spring constant, k_θ, and the masses, M_p and M, with the mass moments of inertia, J_p and J:

$$f_\theta = \frac{1}{2\pi}\left[\frac{k_\theta}{(J_p + 0.3714J)}\right]^{\frac{1}{2}}. \tag{12}$$

The value of J can be found by evaluating the following integral over an appropriate limit:

$$J=\int r^2 dM=\rho h\int\int r^3 d\theta dr. \tag{13}$$

where ρ is the density of polysilicon (2.3×10^3kg·m^{-3}).

The quality factor is estimated similarly to Eq. (10) by assuming Couette flow underneath the plate, and is given by

$$Q = \frac{d(Jk_\theta)^{\frac{1}{2}}}{\mu\int r^2 dA_p} \tag{14}$$

The structures 20, 40 and 45 are frequently fabricated with a four-mask process illustrated in FIG. 4. A significant advantage of this technology is that all the critical features are defined with one mask, eliminating errors due to mask-to-mask misalignment. The process begins with a standard $POCl_3$ blanket n+ diffusion, which defines the substrate ground plane after which a wafer 50 is passivated with a layer 51 of 1500 Å-thick low-pressure chemical-vapor-deposited (LPCVD) nitride deposited on top of a layer 52 of 5000 Å-thick thermal SiO_2 (FIG. 4(*a*)). Contact windows 53 to the substrate ground plane are then opened by a first mask (not shown) (FIG. 4(*b*)) using a combination of plasma and wet etching.

The next steps involve deposition and definition of a first polysilicon layer **54**. A layer **54** of 3000 Å-thick, in situ phosphorus-doped polysilicon is deposited by LPCVD at 650° C., then patterned with a second mask (not shown) (FIGS. 4(*c*) and 4(*d*)). This layer **54** serves as a second electrode plane, the interconnection to the n+ diffusion, and for standoff bumps to prevent sticking of a second polysilicon layer **55** to the substrate **50** after the final micromachining step. A 2 μm-thick LPCVD sacrificial phosphosilicate glass (PSG) layer **56** is deposited and patterned with a third mask, (not shown), as shown in FIGS. 4(*e*) and 4(*f*), which defines the anchors **58** of the microstructures **34**.

A 2 μm-thick polysilicon structural layer **55** is then deposited by LPCVD (undoped) at 605° C. (FIG. 4(*g*)). The structural layer **55** is doped by depositing another layer of 3000 Å-thick PSG **57** (FIG. 4(*h*)) and then annealing at 950° C. for one hour. This doping process is designed to dope the polysilicon layer **55** symmetrically by diffusion from the top and the bottom layers **56** and **57** of PSG. A stress-annealing step is then optionally performed at 1050° C. for 30 minutes in N_2. The annealing temperature is lower than 1100° C. in order to avoid loss of adhesion between the PSG layer **56** and the Si_3N_4**51**.

After stripping the top PSG layer **57** by a timed etch in 10:1 HF, the plates **34**, their beams, and the electrostatic comb drive and sense structures **23** and **24** are defined in the final masking step (FIG. 4(*i*)). The structures **23, 24**, etc. are anisotropically patterned in a CCl_4 plasma by reactive-ion etching, in order to achieve nearly vertical sidewalls. FIG. 4(*j*) illustrates the final cross section after the wafer **50** is immersed in 10:1 diluted HF to etch the sacrificial PSG layer **56**. The movable plate, **44** and a second ground plane **35**, the comb finger **36, 37, 38** and an anchor **58** for the stationary electrode **36, 37** are shown. The wafer **50** is rinsed repeatedly with deionized water for at least 30 minutes after the micromachining step is completed and is then dried in a standard spin dryer.

Surface-micromachined polysilicon structures can become stuck to the substrate after the final drying process. The yield of free-standing structures is zero on wafers for which the 30-minute stress anneal at 1050° C. is omitted. When the stress anneal is included in the process, 70% of the structures are free-standing. The 30% which are initially attached to the substrate could be freed easily with a probe (not shown); the high flexibility of the structures enables manipulation without breakage. No amount of probing, however, could free any of the unannealed structures.

FIG. **6** is a scanning electron micrograph of a serpentine spring supporting a torsional resonant plate. There is no visually observable stiction of the structure to the substrate below.

FIG. **7** is a scanning electron micrograph of a linear resonant structure with 100 μm-long supporting beams and nine fingers on each comb structure. There is no observable buckling of the beams, indicating that built in stress is largely relieved.

FIG. **8** is a scanning electron micrograph of the close-up view of the comb structure in FIG. **9**, showing the details of the comb fingers.

FIG. **9** is a scanning electron micrograph of two two-turn spirals supporting a torsional plate, showing the refined details of spirals and the center anchor point **71**.

FIG. **10** is a scanning electron micrograph of the close-up view of the concentric comb structure in FIG. **9**.

A series of clamped-clamped microbridges (not shown) may be used to estimate the average residual strain in the polysilicon structure from the minimum buckling length. The moment of the residual strain may be qualitatively studied by a series of clamped-free cantilever beams (not shown). Since the microbridges have "step-up" anchors, it is expected that end effects should be modeled carefully to obtain an accurate value of the residual strain. Moreover, the stiction of the diagnostic microbridges and cantilevers to the substrate during drying may also be a source of error in calculating the strain and its moment.

For the unannealed samples, the resultant microcantilevers have a tendency to deflect and attach to the substrate for lengths greater than 150 μm. The buckling length of about 120 μm for microbridges may be interpreted by using the simple clamped-clamped Euler's criterion and estimate the strain as about 10^{-3}. Annealed samples have apparently undeflected cantilevers under optical and SEM observation and have a buckling length of about 220 μm, indicating a residual strain of about 3×10^{-4}. These estimated values are typical of residual strain for phosphorus-doped polysilicon.

These lateral resonant microstructures, with all the associated benefits, such as linear lateral comb drives, stress-relief folded beams, torsional plates with concentric comb drives, and serpentine and spiral spring support arms, can be fabricated from a variety of thin films, such as metals and boron-doped crystalline silicon, using conventional surface and substrate micromachining techniques. The features can be patterned and etched from deposited films or form doped regions of the substrate.

The resonant frequencies, quality factors, and transfer function of such structures with beam lengths of 80 μm or longer can be found by visual observation under 25× magnification. Sinusoidal and dc bias voltages may be applied to the structures via probes contacting the polysilicon pads **21** and **22** in FIG. **1**. For the linear structures, the sinusoidal drive voltage is applied to one set of fixed electrode fingers **36, 37**, etc. via the pad **21**, while a dc bias is supplied to the pad **22** (connected to the dormant sense fingers **24**), and a pad **60** (connected to the first-level polysilicon ground plane and to the suspended structure). The diffused ground plane may be left floating in the initial measurements. The dormant fingers **24** are biased to eliminate electrostatic attraction between them and the resonant structure.

In order to provide large-amplitude lateral motion in air for visual observation, dc biases of up to 40 V and driving voltage amplitudes (zero to peak) of up to 10 V may be used. Resonant frequencies may be determined by maximizing the amplitude of vibration, which can be as large as 10 μm for the linear structures with the longest support beams. The measured resonant frequencies for the linear structures are listed in Table I below and those for the torsional structures are listed in Table II. The results include measurements from two different electrostatic comb structures of FIG. **14** (type A and type B), which are described with Table III.

The calculated resonant frequencies in Tables I and II (and plotted in FIG. **11**) are found from Eqns. (9) and (10) above with the Young's modulus adjusted to give the best fit to the experimental data. For the serpentine-spring torsional structures of FIGS. **5** and **6**, a finite-ele-

ment program may be used to find the effective spring constant. The best-fit value for Young's modulus is E=140 GPa for both linear and torsional resonant structures. From Table I and II, the calculated and measured resonant frequencies are in close agreement for all the lateral structures with beam lengths ranging from 80 μm to 200 μm.

TABLE I

Predicted and Measured Resonant Frequency Values of the Linear Resonant Structures

Beam length [μm]	Type A Predicted [kHz]	Type A Measured [kHz]	Type B Predicted [kHz]	Type B Measured [kHz]
80	75.5	75.0 ± 0.05	71.8	72.3 ± 0.05
100	53.7	54.3 ± 0.05	51.1	50.8 ± 0.05
120	40.6	41.1 ± 0.1	38.7	39.4 ± 0.1
140	32.0	32.0 ± 0.2	30.5	30.0 ± 0.2
160	26.0	25.9 ± 0.2	24.8	25.0 ± 0.2
180	21.7	21.5 ± 0.3	20.7	20.3 ± 0.3
200	18.4	18.2 ± 0.3	17.6	17.5 ± 0.3

TABLE II

Predicted and Measured Resonant Frequency Values of the Torsional Resonant Structures

Supporting Beam Type	Predicted [kHz]	Measured [kHz]
Spiral	10.5	9.7 ± 0.3
Serpent	60.7	59.4 ± 0.2

TABLE III

Types A and B Features

Features	A	B
# of fingers	9	11
Width [μm]	4	4
Gap [μm]	3	2
Fitted $\partial C/\partial x$ [aFμm^{-1}]	58	150

Initial visual measurements of the quality factor Q are plotted in FIG. 13 for the linear resonant structures. The visual measurement of Q is especially difficult for structures with small vibration amplitudes, which is reflected in the larger error bars for these points. The calculated quality factors for Eqn. (10) are consistently higher than the measured values, indicating that the assumption of pure Couette flow is an oversimplification for these structures. However, the calculated values of Q are of the correct magnitude and may be useful for design. The highest measured Q is about 130 for a structure with 80 μm-long folded-beam suspension.

The magnitude of the electromechanical transfer function is measured by estimating the amplitude of vibration from the envelope of the blurred vibrating structure at a given drive voltage and bias voltage. FIG. 12 is a plot of the experimental results of the transfer functions for the linear resonant structures.

The simulation and verification of the resonant modes for these complex microstructures may be desirable. At atmospheric pressure, those modes with motion normal to the substrate are heavily damped, which greatly relaxes the design constraints on the electrostatic comb. For operation in vacuum, design of the drive structure to ensure excitation of a single mode will be challenging, due to the high intrinsic Q of polysilicon microstructures.

What is claimed is:

1. A linear, lateral-drive structure including in combination:
 a substrate,
 a stationary thin-film electrode secured to said substrate and located in a plane thereabove,
 a movable plate overlying said substrate and suspended by flexible supporting arms above said substrate,
 said movable plate and electrode being patterned to provide for each at least one comb with fingers interdigitated with those of the other.

2. The structure of claim 1 wherein the motion of said movable plate is linear.

3. The structure of claim 1 wherein the motion of said movable plate is torsional.

4. The structure of claim 1 having a set of folded beams supporting a linear resonant plate.

5. The said folded beams in claim 4 are anchored near the center of the stucture.

6. The structure of claim 1 having a spiral, anchored at the center of the structure, supporting a torsional resonant plate.

7. The structure of claim 1 having a serpentine spring, supporting a torsional resonant plate.

8. The said serpentine spring in claim 7 is anchored at the center of the structure.

9. The comb structure of claim 1 having comb fingers which are segments of concentric arcs.

10. A resonant microstructure for use as a sensor or an actuator, including in combination:
 a silicon substrate,
 a movable plate, suspended above and anchored to such substrate, and
 lateral-drive means for driving said plate electrostatically in a plane parallel to and above said substrate.

11. The microstructure of claim 10 wherein said lateral-drive means comprises a lateral comb structure for driving said plate with induced electrostatic forces.

12. A lateral-drive structure including in combination:
 a silicon substrate,
 a stationary electrode secured to and elevated above said substrate comprising a plurality of comb fingers, and
 a movable plate suspended by flexible supporting arms in the same plane as said stationary electrodes and comprising a comb with a plurality of fingers on said stationary electrodes.

13. The structure of claim 12 wherein motion of said movable plate is linear.

14. The structure of claim 12 wherein the motion of said movable plate is torsional.

15. The structure of claim 12 having a set of folded beams supporting a linear resonant plate.

16. The said folded beams in claim 15 are anchored near the center of the structure.

17. The structure of claim 15 having a spiral, anchored at the center of the structure, supporting a torsional resonant plate.

18. The structure of claim 12 having a serpentine spring, supporting a torsional resonant plate.

19. The said serpentine spring in claim 18 is anchored at the center of the structure.

20. The comb structure of claim 12 having comb fingers which are segments of concentric arcs.

* * * * *

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Lee (43) **Pub. Date: May 9, 2002**

(54) **OPTICAL SCANNER, LASER IMAGE PROJECTOR ADOPTING THE OPTICAL SCANNER, AND METHOD OF DRIVING THE LASER IMAGE PROJECTOR**

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(52) **U.S. Cl.** **359/223**; 359/201; 359/202; 359/224

(57) **ABSTRACT**

An optical scanner, a laser image projector using the optical scanner, and a method of driving the laser image projector are provided. The optical scanner includes: a base substrate; a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle; a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate; a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes; torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and supports for supporting the torsion bars such that the stage is suspended above the base substrate. The laser image projector includes the optical scanners using micro mirrors, instead of a horizontal scanning rotating polygonal mirror and a vertical scanning galvanometer, and is driven such that a single horizontal left-to-right scanning is followed by another right-to-left horizontal scanning without redundant flyback interval. Therefore, comparing with a driving method which needs quick returning 5-10 times faster than horizontal scanning rate, the driving speed can be markedly reduced, so that high-speed driving limitations of optical scanner for high-resolution image display can be overcome.

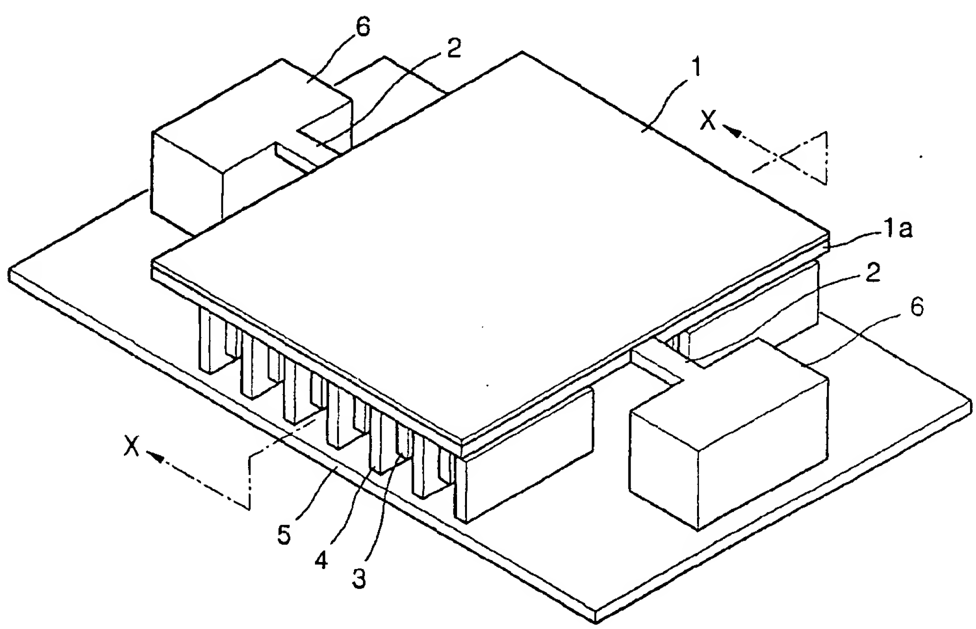


FIG. 1(PRIOR ART)

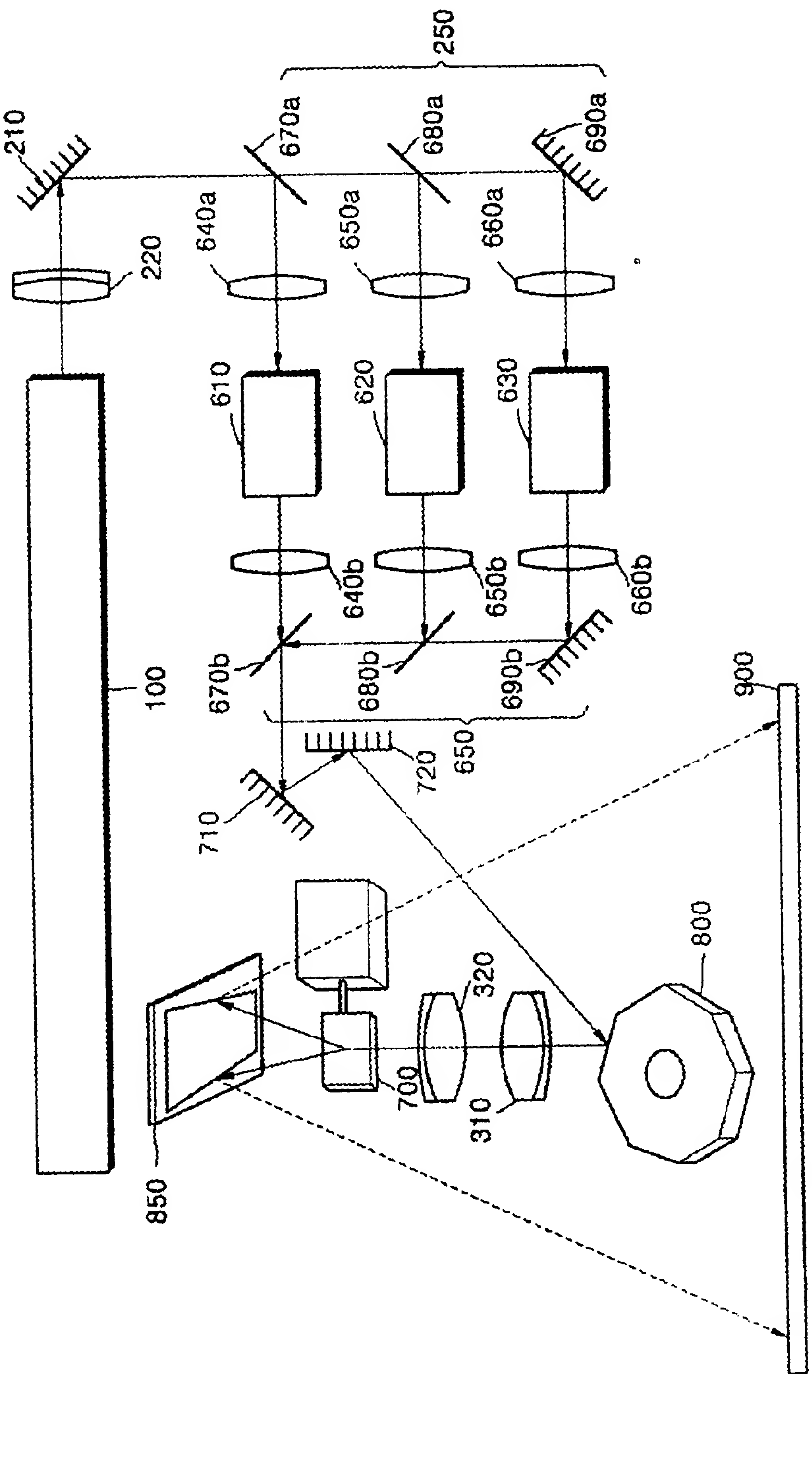


FIG. 2

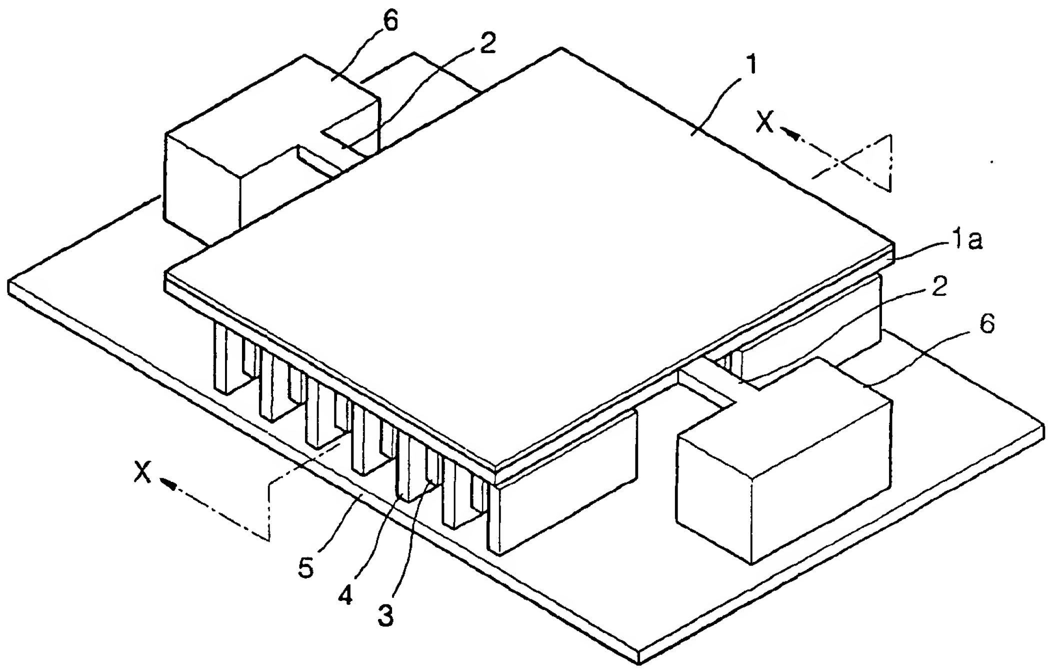


FIG. 3

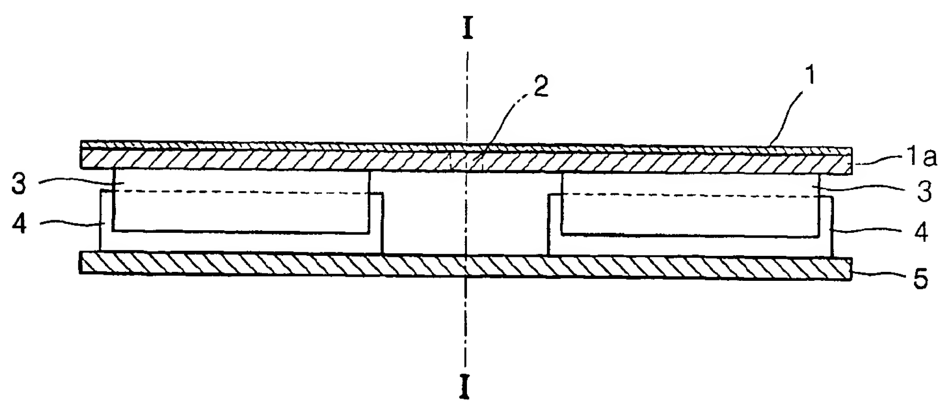


FIG. 4

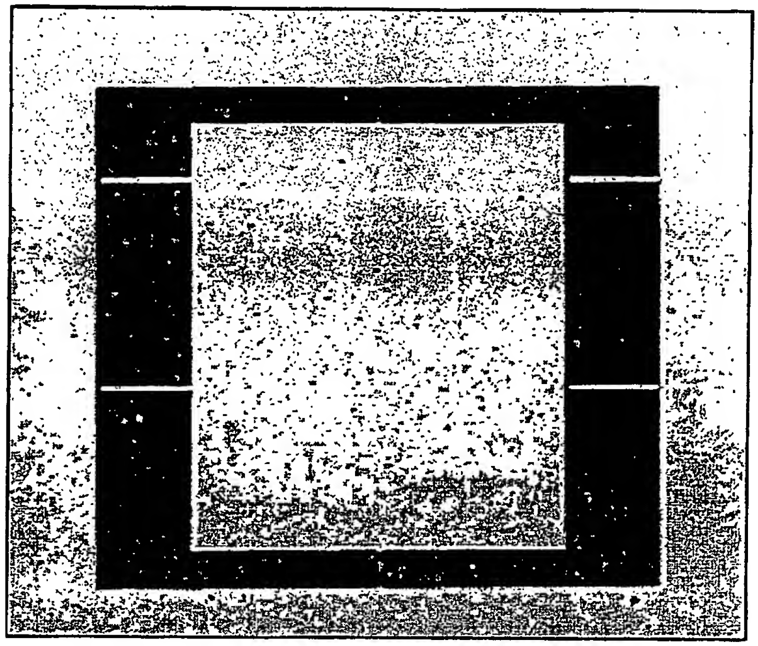


FIG. 5

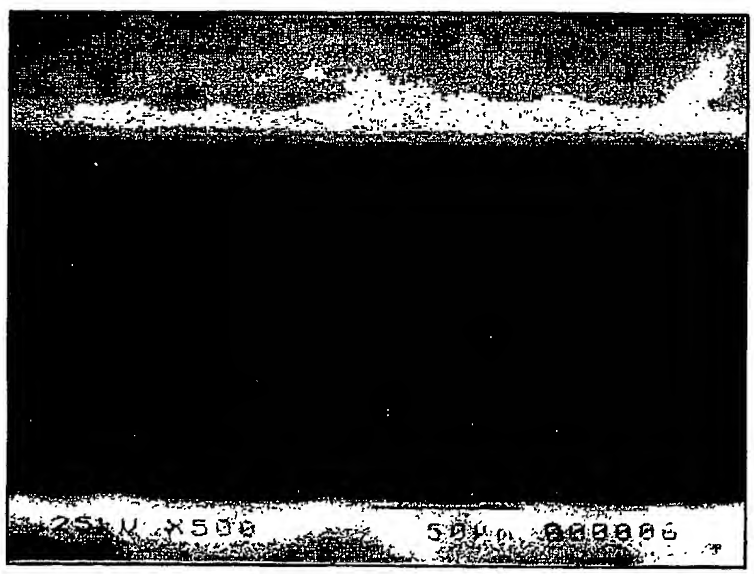


FIG. 6

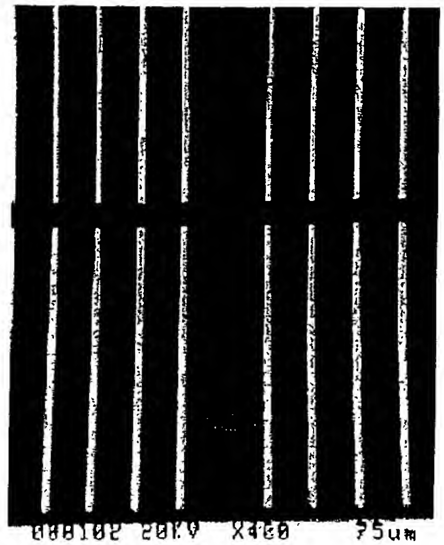


FIG. 7

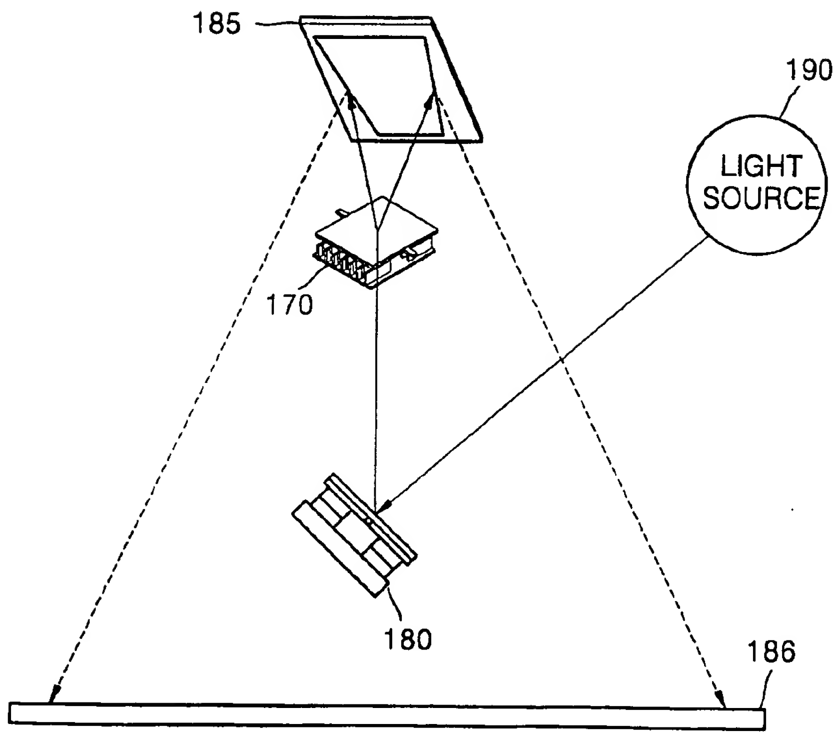
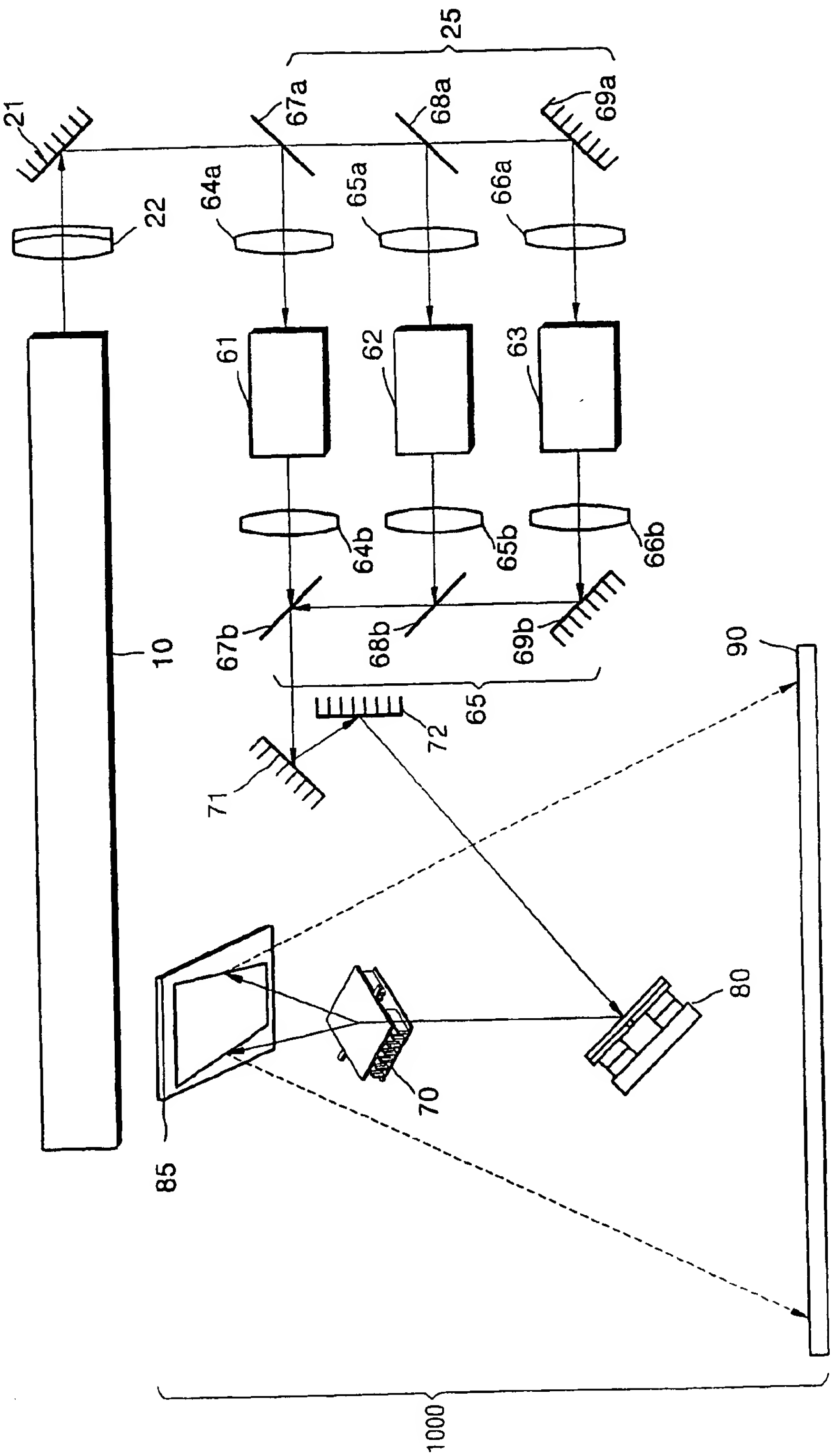


FIG. 8


25
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69a
22
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65a
66a
61
62
63
64b
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80
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85
1000

FIG. 9A (PRIOR ART)

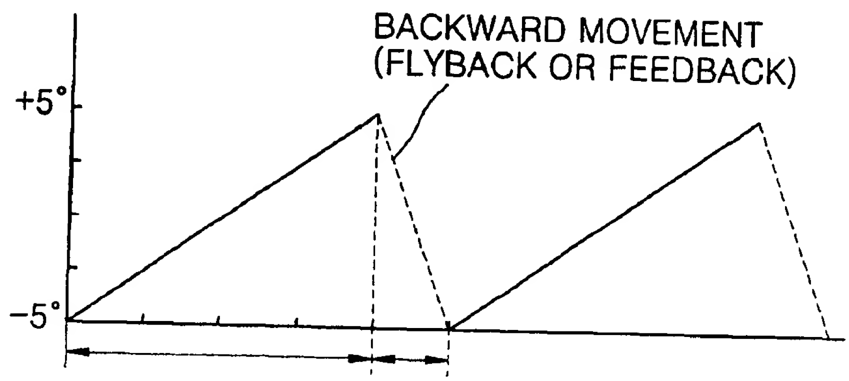


FIG. 9B (PRIOR ART)

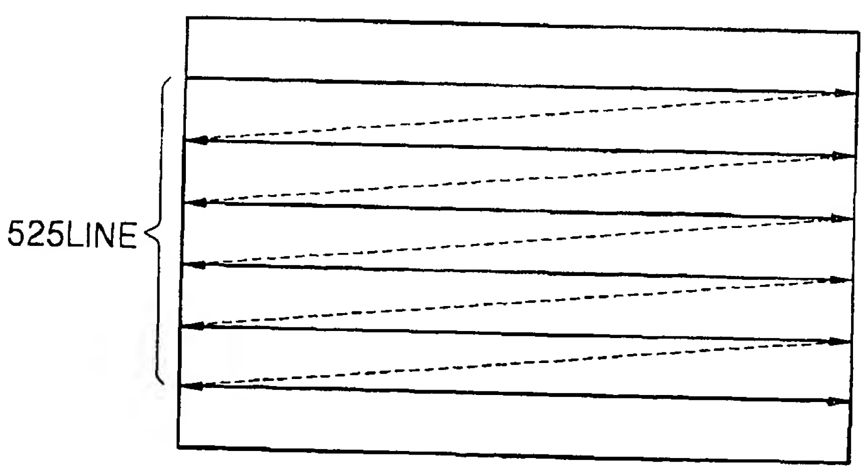


FIG. 10A

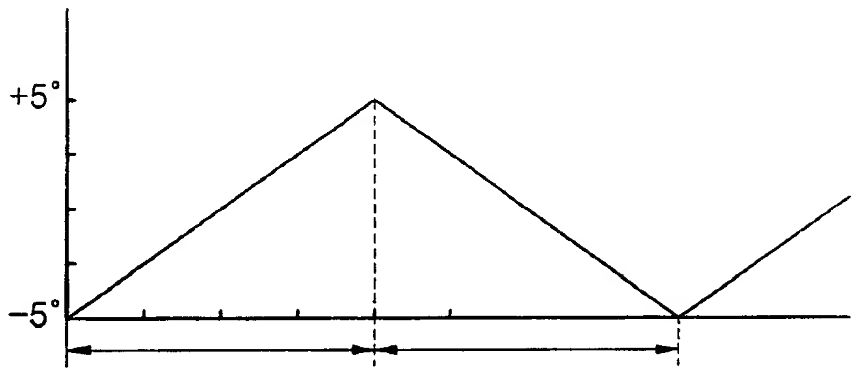
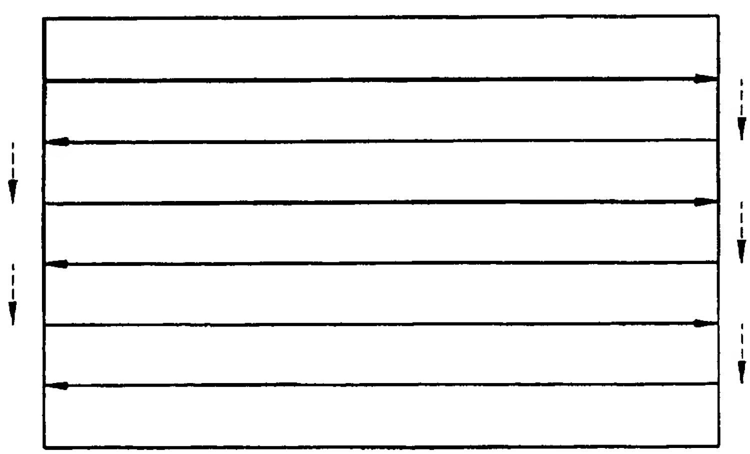


FIG. 10B



OPTICAL SCANNER, LASER IMAGE PROJECTOR ADOPTING THE OPTICAL SCANNER, AND METHOD OF DRIVING THE LASER IMAGE PROJECTOR

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to an optical scanner using micro mirrors based on microelectromechanical system (MEMS) techniques, a laser image projector adopting the optical scanner, and a method of driving the laser image projector, and more particularly, to a multipurpose micro optical scanner, a laser image projector using the optical scanner, which has no limitations in high-speed driving associated with appropriate laser beam scanning onto a screen, and a method for driving the laser image projector.

[0003] 2. Description of the Related Art

[0004] For laser image projectors, a laser beam is scanned in both horizontal and vertical directions to form an image on a screen. For a general NTSC (National Standard System Committee) image signal, a laser beam is scanned horizontally at 15.75 kHz and vertically at 60 Hz. A motion picture consists of 30 image frames per second, and each still image consists of 525 horizontal scan lines (see FIG. 9B). A vertical scanning unit scans once the screen from the top to the bottom while a horizontal scanning unit scans 525 scan lines onto the screen. For the horizontal scanning unit, after horizontal scanning of a single line from the left to the right, there is a need for quickly returning to the left scanning starting point 5-10 times faster than the previous horizontal left-to-right scanning rate so as to prevent light loss.

[0005] FIG. 1 shows the structure of an optical system of a conventional laser image projector. A light source **100** is a white-light laser emitting white light. Semiconductor lasers of red (R), green (G), and blue (B) colors, or a wavelength-convertible solid laser may be used as the light source **100**. A beam separator **250** separates the white light into R, G, and B monochromic beams. The beam separator **250** includes two dichroic mirrors **670***a* and **680***a*, and a high-reflecting mirror **690***a*. The dichroic mirrors **670***a* and **680***a* separate the white light passed through a lens system **220** and an optical path changing high-reflecting mirror **210** into R, G, B beams, and the high-reflecting mirror **690***a* changes the optical path of the monochromic beam passed through the dichroic mirror **680***a*. The separated R, G, and B monochromic beams are focused by focusing lenses **640***a*, **650***a*, and **660***a*, are incident on acousto-optic modulators (AOMs) **610**, **620**, and **630**, respectively, and are modulated based upon an image signal. Collimating lenses **640***b*, **650***b*, and **660***b* for collimating the modulated laser beams back into the same parallel beams as those before entering the focusing lenses **640***a*, **650***a*, and **660***a* are disposed next to the AOMs **610**, **620**, and **630**. The R, G, and B beams modulated based upon the image signal are combined into a single combined beam by a beam combinder **650**. The beam combinder **650** includes two dichroic mirrors **670***b* and **680***b*, and a high-reflecting mirror **690***b*. The combined beam is incident on a polygonal mirror **800** at an appropriate angle by high-reflecting mirrors **710** and **720**. As the combined beam is incident on the polygonal mirror **800** serving as a horizontal scanning unit, the combined beam is horizontally scanned. A horizontal scanning beam passes through relay lenses **310** and **320**, which are disposed between the polygonal mirror **800** and a galvanometer **700**, and is focused on a mirror side of the galvanometer **700**. A laser beam spot focused on the galvanometer **700** is vertically scanned. An image scanned by the polygonal mirror **800** and the galvanometer **700** is projected onto a screen **900** by a reflecting mirror **850** which is disposed above the galvanometer **700** facing the screen **900**.

[0006] For the conventional laser image projector having the configuration above, the rotating polygonal mirror **800** is used as a horizontal scanning unit. The rotating polygonal mirror **800** is advantageous in that there is no need for quick returning to the initial scanning point described above. However, the polygonal mirror **800** is mechanically rotated, so that there are limitations in increasing the scanning rate and reducing the size. Thus, a small laser television (TV) cannot be implemented with the polygonal mirror **800**. For this reason, a micro optical scanner having a structure of MEMS-technique based microactuator has been suggested as a horizontal scanning unit for a small laser TV. However, unlike a mechanical rotational driving method, for a general galvanometer driving method, a return (or flyback) period 5-10 times shorter than a single horizontal line scanning period is required. However, it is very difficult to manufacture a micro optical scanner which satisfies the need for such quick returning.

[0007] U.S. Pat. No. 5,025,346 discloses a micro actuator using the electrostatic effect by comb electrodes. This micro actuator includes movable comb electrodes formed on a movable structure, and stationary comb electrodes formed on a stationary structure, wherein the movable and stationary comb electrodes are alternately arranged. The movable structure is suspended by neighboring supports. This suspension structure oscillates at a horizontal resonant frequency.

[0008] For an x-y axial driving, i.e., along two or more axises, more electrodes are required for a driving unit. For example, the driving unit includes at least three electrodes for an one-axial and unidirectional driving, and at least five electrodes for an one-axial and bidirectional driving. U.S. Pat. No. 5,536,988 discloses a multi-axial driving micro actuator as a driving unit having a plurality of electrodes, which is formed in selective areas of a silicon substrate by a thermal-oxidation insulating method.

[0009] The conventional micro actuator includes parallel driving comb electrodes formed along the edge of a movable stage or structure, and parallel stationary comb electrodes fixed on a stationary stage. The stationary comb electrodes and the driving comb electrodes are alternately arranged facing each other.

[0010] The conventional micro actuators having the configurations have comb electrodes around the edge of the stages, so that the size of the entire microactuating system is enlarged with respect to the stages or movable structure, thereby limiting the applications thereof.

SUMMARY OF THE INVENTION

[0011] It is a first object of the present invention to provide a miniature optical scanner in which the structure of comb electrodes is efficiently designed.

[0012] It is a second object of the present invention to provide a multipurpose optical scanner capable of linear or 2-dimensional scanning.

[0013] It is a third object of the present invention to provide a laser image projector adopting the optical scanner having a micro mirror and a method of driving the laser image projector, in which the scanning direction of a horizontal scan line is alternately changed to eliminate a redundant flyback period, so that correct image reproduction can be achieved at a relatively low driving speed.

[0014] To achieve the first and second objects of the present invention, there is provided an optical scanner comprising: a base substrate; a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle; a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate; a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes; torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and supports for supporting the torsion bars such that the stage is suspended above the base substrate.

[0015] In another embodiment, there is provided an optical scanner comprising: a first optical scanner having a reflecting side from which an incident beam is reflected in a first direction within the range of a predetermined angle; and a second optical scanner for scanning a laser beam scanned by the first optical scanner in the first direction, in a second direction perpendicular to the first direction, wherein each of the first and second optical scanners comprises: a base substrate; a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle; a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate; a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes; torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and supports for supporting the torsion bars such that the stage is suspended above the base substrate.

[0016] According to an aspect of the third object of the present invention, there is provided a laser image projector comprising: a light source for emitting a white light beam; a beam separating unit for separating the white light beam into three main monochromic beams; an acousto-optic modulating unit for modulating the three main monochromic beams based on color signals; a beam combining unit for combing the monochromic beams modulated by the acousto-optic modulating unit into a single combined beam; and a laser scanning unit for scanning the single beam combined with the monochromic beams to form an image, wherein the laser scanning unit comprises a horizontal scanning mirror for horizontally scanning the single combined beam, and a vertical scanning mirror for vertically scanning a beam incident from the horizontal scanning mirror.

[0017] In the laser image projector, it is preferable that the laser scanning unit comprises a first optical scanner having the horizontal scanning mirror and a second optical scanner having the vertical scanning mirror, wherein each of the first and second optical scanners comprises: a base substrate; a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle, a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate; a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes; torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and supports for supporting the torsion bars such that the stage is suspended above the base substrate.

[0018] It is preferable that the horizontal scanning mirror horizontally scans the single beam combined with the monochromic beams alternately from the left to the right and from the right to the left. It is preferable that the laser scanning unit further comprises a memory for temporarily storing an image information horizontally scanned from the right to the left.

[0019] According to another aspect of the third object of the present invention, there is provided a method of driving a laser image projector including: a light source for emitting a white light beam; a beam separating unit for separating the white light beam into three main monochromic beams; an acousto-optic modulating unit for modulating the three main monochromic beams based on color signals; a beam combining unit for combing the monochromic beams modulated by the acousto-optic modulating unit into a single combined beam; and a laser scanning unit for scanning the single beam combined with the monochromic beams to form an image, the method comprising alternately horizontally scanning the single beam combined with the modulated monochromic beams from the left to the right and from the right to the left.

[0020] It is preferable that an image signal scanned in opposite directions to an input image signal in the alternate horizontal scanning from the left to the right and from the right to the left is temporarily stored in a memory and is output in the reverse order such that a correct image can be displayed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The above objects and advantages of the present invention will become more apparent by describing in detail preferred embodiments thereof with reference to the attached drawings in which:

[0022] FIG. 1 is a schematic view of a conventional laser image projector;

[0023] FIG. 2 is a perspective view of a preferred embodiment of an optical scanner according to the present invention;

[0024] FIG. 3 is a sectional view of the optical scanner according to the present invention taken along line X-X of FIG. 2;

[0025] FIG. 4 is a photograph of an actual optical scanner according to the present invention;

[0026] FIG. 5 is a photograph of an actual optical scanner according to the present invention, which shows the arrangement of driving comb electrodes on the bottom of a stage and of stationary comb electrodes on the top of a substrate;

[0027] FIG. 6 is a photograph of an actual optical scanner according to the present invention, which shows the stationary comb electrodes are divided into two groups on the substrate;

[0028] **FIG. 7** is a schematic view of another preferred embodiment of the optical scanner, which adopts two optical scanner units of **FIG. 2**;

[0029] **FIG. 8** is a schematic view of a laser image projector according to the present invention having optical scanners with micro mirrors;

[0030] **FIGS. 9A and 9B** illustrate a conventional horizontal scanning method, and in particular, **FIG. 9A** shows a conventional horizontal scan signal, and **FIG. 9B** shows the scanning direction onto a screen depending on the horizontal scan signal of **FIG. 9A**; and

[0031] **FIGS. 10A and 10B** illustrate a horizontal scanning method according to the present invention, and in particular, **FIG. 10A** shows a horizontal scan signal, and **FIG. 10B** shows the scanning direction onto a screen depending on the horizontal scan signal of **FIG. 10A**.

DETAILED DESCRIPTION OF THE INVENTION

[0032] A preferred embodiment of an optical scanner according to the present invention is shown in **FIGS. 2 and 3**. Referring to **FIG. 2**, a stage **1***a* is suspended by supports **2** above a substrate **5** made of, for example, pyrex glass. Here, the both sides of the stage **1***a* is supported by the supports **2**. Torsion bars **2** are located in the middle of the sides of the stage **1***a* and support the stage **1** such that the stage **1** can pivot like a seesaw. The torsion bars **2** are connected to the supports **6**.

[0033] As shown in **FIG. 3**, the top of the stage **1***a* is formed by a mirror side **1**. A plurality of parallel driving comb electrodes **3** are formed on the bottom of the stage **1***a* to have a predetermined height. The plurality of driving comb electrodes **3** are divided into two groups by line I-I.

[0034] On the other hand, a plurality of parallel stationary comb electrodes **4** are formed on the top of the substrate **5** to have a predetermined height, which are perpendicular to the driving comb electrodes **3**. The plurality of stationary comb electrode **3** are also divided into two groups by line I-I aligned with the driving comb electrodes **3**.

[0035] In the optical scanner having the configuration, the stage **1***a* oscillates by electrostatic force exerted between the driving comb electrodes **3** and the stationary comb electrodes **4** which are divided by line I-I. For example, if an attractive force acts between the driving comb electrodes **3** and the stationary comb electrodes **4** arranged on the left of line I-I, the stage **1***a* rotates to the left. Meanwhile, if an attractive force acts between the driving comb electrodes **3** and the stationary comb electrodes **4** arranged on the right of line I-I, the stage **1***a* rotates to the right. The stage **1***a* returns to its original position by self-restoring force based on the elastic modulus of the torsion bars **2**. The electrostatic force is induced with alternate applications of voltage to the left and right sides, so that the stage **1***a* oscillates.

[0036] In **FIGS. 2 and 3**, a wiring layer for supplying an electric signal to the driving comb electrodes **2** and the stationary comb electrodes **4** is not illustrated. The main wiring layer for the driving comb electrodes **3** and the stationary comb electrodes **4** is formed in the substrate **5**. An electric signal for the driving comb electrodes **3** is supplied by the wiring layer formed on the substrate **5**, the supports **6**, and the stage **1***a*. The wiring layer can be easily formed by a common technique, and thus description of the wiring layer formation will not be provided here.

[0037] **FIG. 4** is a photograph of an actual optical scanner according to the present invention, which is manufactured as a sample. **FIG. 5** is a photograph of the arrangement of the driving comb electrodes **3** formed on the bottom of the stage **1***a* and the stationary comb electrodes **4** formed on the top of the substrate **5**. **FIG. 6** is a photograph of the arrangement of the stationary comb electrodes **4** formed on the substrate **5**, in which the stationary comb electrodes **4** are divided into two groups, as described previously. This divided structure is also shown for the driving comb electrodes **3** formed on the bottom of the stage **1***a*.

[0038] The optical scanner having the configuration described above can be used for multiple purposes. For example, a single or a plurality of optical scanners can be applied to a laser image projector according to the present invention, which will be described later, a laser printer which needs linear laser beam scanning, and a bar code reader. For linear scanning, one optical scanner is adopted. For 2-dimensional planar scanning, at least two optical scanners are used. In this case where an apparatus employs two optical scanners, one of the optical scanners scans a laser beam in the x-direction, and the other optical scanner performs scanning in the y-direction with the beam scanned in the x-direction. Therefore, an image can be displayed by scanning a planar screen with laser beam, or a linear light signal can be obtained from an image of an object scanned.

[0039] **FIG. 7** is a schematic view of a multipurpose 2-dimensional optical scanner adopting two optical scanner units according to another preferred embodiment of the present invention. Referring to **FIG. 7**, a first optical scanner **180** for scanning a light beam in a first direction is located forward of a light source **190** which emits a light beam in a constant direction. The first optical scanner **180** reflects the beam incident from the light source **190** in the x-direction within the range of a predetermined angle. A second optical scanner **170** is located on the travelling path of the reflected beam from the first optical scanner **180** to reflect the beam reflected by the first optical scanner **180** in the y-direction perpendicular to the x-direction.

[0040] A reflecting mirror **185** is disposed on the travelling path of the reflected beam from the second optical scanner **170**. An image screen **186** on which the light beam is finally incident is located on the travelling path of beam reflected from the reflecting mirror **185**. Alternatively, the image screen **186** may be located in the position of the reflecting mirror **185**. In this case, the reflecting mirror **185** is not mounted.

[0041] Although the optical scanner of **FIG. 7** is illustrated as structure in which a planar image is formed using the point light source, the optical scanner may be constructed in the reverse structure. In particular, the image screen **186** may be an object to be scanned and the light source **190** may be replaced with a photodetector. In this case, the optical scanner acts as an image scanner for reading an image of the object as a linear electrical signal. This image scanner may be used as a general image scanner for generating a computer image file from a photograph, or as a bar code reader for reading product bar codes. In other words, for the optical scanner according to the present

invention having the configuration shown in **FIG. 7**, the beam travelling direction can be changed depending on the purpose of use and appropriate optical elements can be disposed at the ends of the beam travelling path of the optical scanner according to the changes.

[0042] Hereinafter, a preferred embodiment of a laser image projector according to the present invention, which adopts two optical scanners having the configuration described above, will be described in greater detail. In the laser image projector according to the preset invention, a laser scanning unit (LSU) using micro mirror continues to scan along horizontal scan lines by alternately changing the scanning direction without need for flyback interval. As a result, normal image reproduction can be implemented with the optical scanner having a relatively low scanning rate. To this end, an image signal scanned in the opposite direction is stored in a buffer memory and is output in the reverse order to display the correct image. The structure of the laser image projector according to the present invention will be described below in detail.

[0043] **FIG. 8** shows the optical structure of a laser image projector according to the present invention having optical scanners with micro mirrors. Referring to **FIG. 8**, a light source **10** is a white-light laser emitting white light. Semiconductor laser devices of red (R), green (G), and blue (B) colors, or a wavelength-convertible laser may be used as the light source **10**. A beam separator **25** separates the white light passed through a lens system **22** and an optical path changing mirror **21** into R, G, and B monochromic beams. The beam separator **25** includes two dichroic mirrors ***67a*** and ***68a***, and a high-reflecting mirror ***69a***. The dichroic mirrors ***67a*** and ***68a*** separate the white light into R, G, B beams, and the high-reflecting mirror ***69a*** changes the optical path of the monochromic beam passed through the dichroic mirror ***68a***. The separated R, G, and B monochromic beams are focused by focusing lenses ***64a***, ***65a***, and ***66a***, are incident on acousto-optic modulators (AOMs) **61**, **62**, and **63**, respectively, and are modulated based upon an image signal. Collimating lenses ***64b***, ***65b***, and ***66b***, for collimating the modulated laser beams back into the same parallel beams as those before entering the focusing lenses ***64a***, ***65a***, and ***66a***, are disposed next to the AOMs **61**, **62**, and **63**. The R, G, and B beams modulated based upon the image signal are combined into a single combined beam by a beam combinder **65**. The beam combinder **65** includes two dichroic mirrors ***67b*** and ***68b***, and a high-reflecting mirror ***69b***. The combined beam is incident on a horizontal scanning mirror **80** of a laser scanning unit (LSU) **1000** which is a feature element of the present invention. In particular, the combined beam is incident on the horizontal scanning mirror **80** of the LSU **1000**, and is horizontally scanned. The horizontal scanning beam is focused on a mirror side of a vertical scanning mirror **70** of the LSU **1000** and is vertically scanned. An image scanned by the horizontal and vertical scanning mirrors **80** and **70** is projected onto a screen **90** by a reflecting mirror **85** which is disposed above the vertical scanning mirror **70**.

[0044] The LSU **1000** including the horizontal scanning mirror **80**, the vertical scanning mirror **70**, and the reflecting mirror **85** is manufactured as a micro structure using microelectromechanical system (MEMS)-techniques. A MEMS-technique based optical scanner has the structure described with reference to **FIGS. 2 through 6**. Thus, the LSU **1000** includes the optical scanners whose structure has been described previously. In particular, the vertical scanning mirror **70** and the horizontal scanning mirror **80** are formed as separate optical scanners. The functions of the vertical scanning mirror **70** and the horizontal scanning mirror **80** are performed by the mirror side **1** of the stage ***1a*** of the optical scanner described previously.

[0045] The ultimate goal of the present invention is to implement a laser TV receiver by reducing the size of a laser image projector therefor using such micro optical scanners. By replacing the polygonal mirror and galvanometer which serve as the conventional LSUs with two miniature optical scanners having micro mirrors with application of a driving method suitable for high-speed image process, it is possible to implement a high-quality laser TV.

[0046] A method of driving the laser image projector according to the present invention will be described with reference to **FIGS. 10A and 10B** in comparison with the conventional driving method illustrated in **FIGS. 9A and 9B**. **FIGS. 9A and 10A** show a conventional horizontal scan signal and a horizontal scan signal according to the present invention, respectively. **FIGS. 9B and 10B** show the scanning directions of laser beam onto a screen according to the conventional horizontal scan signal and the horizontal scan signal according to the present invention, respectively. For the conventional horizontal scan signal, in the solid line interval of the horizontal scan signal, as shown in **FIG. 9A**, a single horizontal line denoted by a solid line in **FIG. 9B** is scanned from the left to the right. After the single line scanning, in the dashed line interval of **FIG. 9A**, the laser beam returns to the initial scanning starting position, toward the left, 5-10 times faster than the left-to-right horizontal scanning rate, along a dashed line of **FIG. 9B**. The conventional driving method displays an image by sequentially repeating the left-to-right horizontal scanning and the right-to-left horizontal flyback movement. For the conventional driving method, high-speed horizontal scanning is required for high-resolution image display. However, there is a limitation of increasing scanning rate with the optical scanner.

[0047] On the contrary, for the laser image projector according to the present invention in which the micro horizontal scanning mirror is used instead of the polygonal mirror serving as a conventional horizontal scanning unit for miniaturization purpose, the micro horizontal scanning mirror operates based on the horizontal scan signal illustrated in **FIG. 10A**. As shown in **FIG. 10A**, this horizontal scan signal has no flyback interval as illustrated with only solid lines. The present invention is characterized in that continuous horizontal scanning without flyback interval is possible. Thus, as shown in **FIG. 10B**, on the basis of the horizontal scan signal of **FIG. 10A**, a single left-to-right horizontal scanning is followed by another right-to-left horizontal scanning. The entire of an image is realized by repeating the left-to-right horizontal scanning and the right-to-left horizontal scanning, the entire of an image is realized. According to the driving method of the present invention, the horizontal scanning can be continuously performed without the redundant flyback interval which is inevitable for the conventional driving method. Thus, although the scanning rate of micro mirror of the laser image projector according to the present invention is lower than the conventional scanning unit, the correct image can be realized. In other words, when the scanning manner illustrated in **FIG. 10B** is

applied to the micro optical scanner according to the present invention, there is no need for quick returning to the initial scanning starting position (flyback mode), so that the correct image can be displayed with high-resolution beyond the limitation associated with high-speed driving of optical scanner. In the present invention, a line of the image scanned from the right to the left is opposite to the original input image signal, so that the transmitted image signal is stored in a buffer memory and is output in the reverse order to display the correct image. According to the present invention, the driving method which needs no flyback interval following a single horizontal scanning is applied to the micro optical scanner, so that satisfactory image display can be implemented even at relatively low driving speed.

[0048] As previously described, the optical scanner according to the present invention is characterized in terms of its miniature structure, so that its applications can be extended. The laser image projector according to the present invention includes the optical scanners using micro mirrors, instead of the horizontal scanning rotating polygonal mirror and the vertical scanning galvanometer, and is driven such that a single horizontal left-to-right scanning is followed by another right-to-left horizontal scanning without redundant flyback interval. Therefore, comparing with the conventional driving method which needs quick returning 5-10 times faster than horizontal scanning rate, the driving speed can be markedly reduced, so that high-speed driving limitations of optical scanner for high-resolution image display can be overcome. In addition, the left-right balanced driving manner contributes to preventing damage of the optical scanner with improved reliability.

[0049] While this invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. An optical scanner comprising:

a base substrate;

a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle;

a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate;

a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes;

torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and

supports for supporting the torsion bars such that the stage is suspended above the base substrate.

2. An optical scanner comprising:

a first optical scanner having a reflecting side from which an incident beam is reflected in a first direction within the range of a predetermined angle; and

a second optical scanner for scanning a laser beam scanned by the first optical scanner in the first direction, in a second direction perpendicular to the first direction,

wherein each of the first and second optical scanners comprises:

a base substrate;

a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle;

a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate;

a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes;

torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and

supports for supporting the torsion bars such that the stage is suspended above the base substrate.

3. The optical scanner of claim 2, wherein a light source for emitting a beam onto the first optical scanner is disposed forward of the first optical scanner, and an image screen is disposed on the traveling path of a beam reflected from the second optical scanner.

4. The optical scanner of claim 3, wherein a reflecting mirror for reflecting a beam from the second optical scanner toward the image screen is disposed between the second optical scanner and the image screen.

5. The optical scanner of claim 2, wherein a photodetector is disposed at the end of the optical path close to the first optical scanner, and an object to be scanned is located at the other end of the optical path close to the second optical scanner.

6. A laser image projector comprising:

a light source for emitting a white light beam;

a beam separating unit for separating the white light beam into three main monochromic beams;

an acousto-optic modulating unit for modulating the three main monochromic beams based on color signals;

a beam combining unit for combing the monochromic beams modulated by the acousto-optic modulating unit into a single combined beam; and

a laser scanning unit for scanning the single beam combined with the monochromic beams to form an image,

wherein the laser scanning unit comprises a horizontal scanning mirror for horizontally scanning the single combined beam, and a vertical scanning mirror for vertically scanning a beam incident from the horizontal scanning mirror.

7. The laser image projector of claim 6, wherein the laser scanning unit comprises a first optical scanner having the horizontal scanning mirror and a second optical scanner having the vertical scanning mirror,

wherein each of the first and second optical scanners comprises:

a base substrate;

a plurality of parallel stationary comb electrodes arranged on the base substrate extending upwards at right angle;

a stage having a mirror side at its top side, being separated a predetermined distance above the base substrate;

a plurality of parallel driving comb electrodes arranged on the bottom of the stage extending at right angle interdigitated with the stationary comb electrodes;

torsion bars formed at both side edges of the stage with a predetermined length to support such that the stage pivots; and

supports for supporting the torsion bars such that the stage is suspended above the base substrate.

8. The laser image projector of claim 6, wherein the horizontal scanning mirror horizontally scans the single beam combined with the monochromatic beams alternately from the left to the right and from the right to the left.

9. The laser image projector of any of claims **6** through **8**, wherein the laser scanning unit further comprises a memory for temporarily storing an image information horizontally scanned from the right to the left.

10. The laser image projector of any of claims **6** through **8**, wherein the three monochromic beams have a wavelength of 450-470 nm, a wavelength of 530-535 nm, and a wavelength of 630-650 nm, respectively.

11. The laser image projector of claim 10, wherein the three monochromic beams have a wavelength of 457 nm, a wavelength of 532 nm, and a wavelength of 635 nm, respectively.

12. The laser image projector of claim 9, wherein the three monochromic beams have a wavelength of 450-470 nm, a wavelength of 530-535 nm, and a wavelength of 630-650 nm, respectively.

13. The laser image projector of claim 12, wherein the three monochromic beams have a wavelength of 457 nm, a wavelength of 532 nm, and a wavelength of 635 nm, respectively.

14. A method of driving a laser image projector including: a light source for emitting a white light beam; a beam separating unit for separating the white light beam into three main monochromic beams; an acousto-optic modulating unit for modulating the three main monochromic beams based on color signals; a beam combining unit for combing the monochromic beams modulated by the acousto-optic modulating unit into a single combined beam; and a laser scanning unit for scanning the single beam combined with the monochromic beams to form an image, the method comprising alternately horizontally scanning the single beam combined with the modulated monochromic beams from the left to the right and from the right and the left.

15. The method of claim 13, wherein an image signal scanned in opposite directions to an input image signal in the alternate horizontal scanning from the left to the right and from the right to the left is temporarily stored in a memory and is output in the reverse order such that a correct image can be displayed.

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